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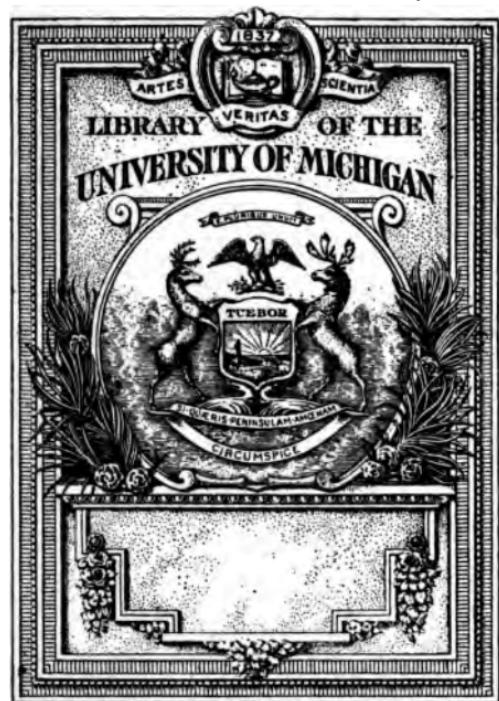
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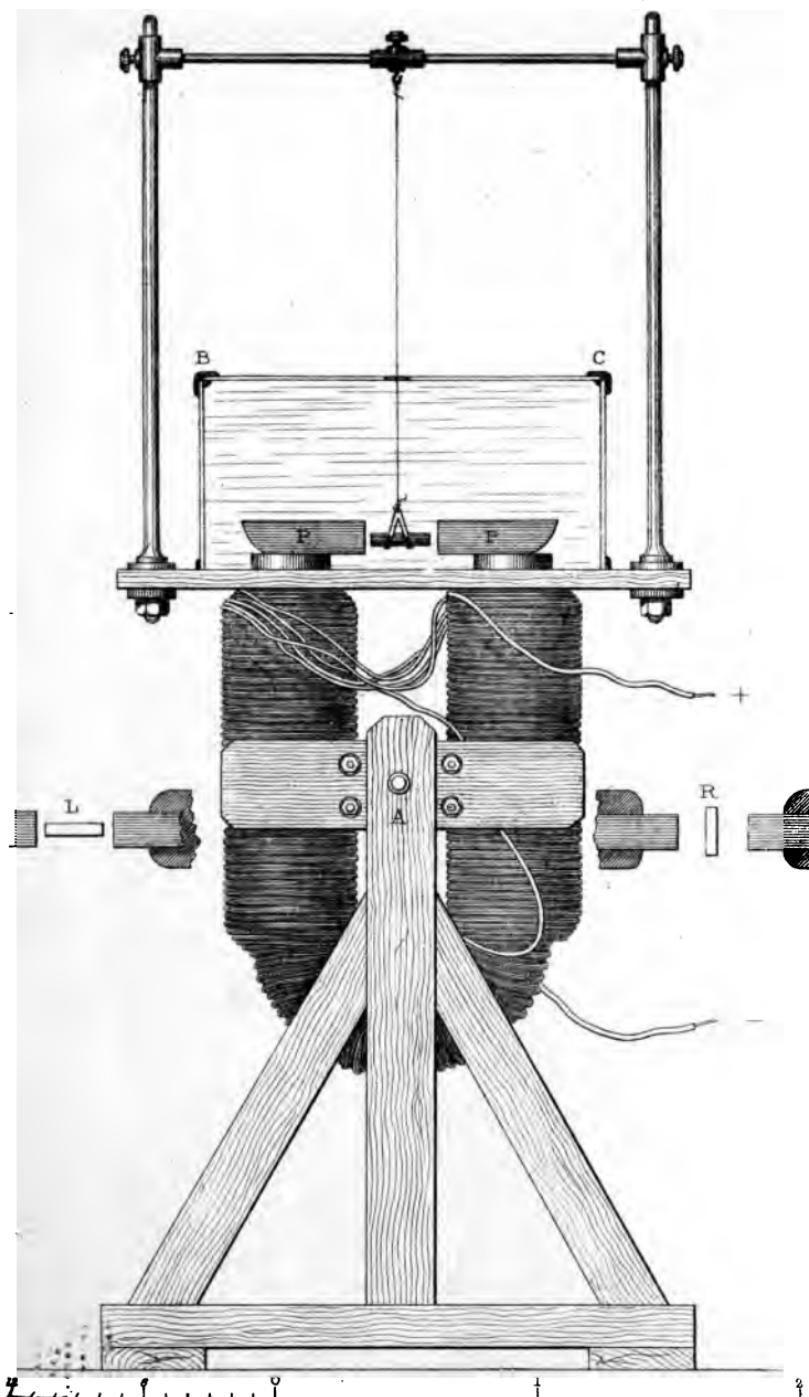
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R. J. Glazebrook Esq
from the Author

DIAMAGNETISM
AND
MAGNE-CRYSTALLIC ACTION

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THE ROYAL INSTITUTION MAGNET.

London: Longmans & Co.

THE
DIAGNOSTIC
TESTS

FOR
DIAGNETISM

1888

MAGNETOCRYSTALLIC ACTION

INCLINED PLANE TESTS

DIAGNETIC TESTS

1888

JOHN TYNDALL, D.C.L., LL.D., F.R.S.

NEW EDITION

LONDON

LONGMANS, GREEN, AND CO.

1888

Frontispiece.

THE ROYAL INSTITUTION MAGNET.
London: Longmans & Co.

RESEARCHES ON
DIAMAGNETISM
AND
MAGNE-CRYSTALLIC ACTION

INCLUDING THE QUESTION OF
DIAMAGNETIC POLARITY

BY
JOHN TYNDALL, D.C.L., LL.D., F.R.S.

NEW EDITION

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1888

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TO
PROFESSOR WILHELM WEBER,
OF GÖTTINGEN,
WITH THE DEEP RESPECT OF ITS AUTHOR,
THIS BOOK IS DEDICATED.

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PREFACE

TO

THE NEW EDITION.

BEGUN in Marburg, continued in Berlin, and ended in the quiet laboratory of the Royal Institution, the researches here presented to the reader cover the first six years of my experimental work. It was difficult work, and the discipline it involved was of high value to me as a preparation for labours more difficult still. The forces to be investigated were so weak, and their action was so complex, that in dealing with them the extreme of delicacy had to be combined with the maximum of power. Hence, indeed, the divergences and discussions which, for several years, the questions here considered provoked among eminent scientific men. At the time referred to, the subject was one of universal interest; which, in view of its theoretic significance, is sure, in due time, to reappear.

The first investigation of the series, conducted in companionship with my friend Professor Knoblauch, treats of the deportment of crystals, and of other bodies possessing a definite structure, in the magnetic field. Plücker had discovered that deportment, and had deduced from it the existence of new forces and new laws, having an important bearing not only on the phenomena of magnetism, but on those of light. Faraday followed Plücker and verified

him, adding, moreover, another to the list of forces already assumed. These forces were alleged to possess an individuality wholly distinct from magnetism and diamagnetism. Special experiments, indeed, were executed by Faraday, to prove that neither attraction nor repulsion had anything to do, and, as a consequence, that *polarity* could have nothing to do, with the phenomena.

This conclusion landed him in serious difficulty, and his musings on the insoluble enigma thereby created are profoundly interesting. He visualises the crystalline particles, and the power which makes them cohere in regular order. He looks at his magnet in relation to these particles and to this power; and he concludes that it is impossible to conceive of the results otherwise than as being due to the interaction of the magnetic force and the forces which built the crystal. This was his way of looking at the problem. To him, as he reflects upon it, the magne-crystallic force appears 'to be very strange and striking in its character. It is not polar, for there is no attraction or repulsion. What then is the nature of the force which turns the crystal round, and makes it affect a magnet? I do not remember,' he continues, 'such a case of force as the present one, where a body is brought into position only, without attraction or repulsion.' After advancing what he considers to be 'a very striking series of proofs that neither attraction nor repulsion governs' the conduct of crystals in the magnetic field, he winds up with the emphatic inference that this new force 'is distinct in its character from the magnetic and diamagnetic forms of force.'

So thought, and so reasoned, this incomparable experimenter. His views were assuredly strange, but they brought into play the driving-force of his emotions. Here, as in many other cases, the very strangeness of Faraday's conclusions constituted a stimulus which urged him into regions where the art and instinct of the experimenter

were supreme, and from which he was sure to return enriched with the spoils of discovery.

In the researches here thrown together the experiments of Plücker on crystals are carefully repeated and greatly multiplied in number. Standing as a mathematician in his own department, in the first rank, and fortunate, beyond many, in the discovery of facts, his conclusions from his experiments were, at the beginning, precipitate. His first striking generalization, indeed, was corrected by himself; but his second statement of the law of magne-crystallic action was as faulty as the first. Pasteur truly describes the art of experiment as beset with difficulty and danger. Plücker, when he passed suddenly from mathematics to physics, was not sufficiently aware of this. He did not give himself sufficient time to vary his combinations, and check his results, before publishing his conclusions. Still, he must, I think, be credited with a large measure of that experimental instinct, which, in Faraday, rose to the dignity of a new sense, enabling him to see in each fact extensions and applications beyond the discernment of ordinary men.

Plücker concluded that the magnetic deportment of a crystal, and its optical deportment, went hand in hand—that from either of them the other could be inferred. He announced the important law that *negative* crystals, when suspended in the magnetic field with their optic axes horizontal, took up, on the development of the magnetic force, a definite position—always setting the optic axes at right angles to the direction of the magnetic force; while *positive* crystals, under the same influence, set their axes from pole to pole. In the latter case the axes were said to be *attracted*, in the former case, *repelled*. This was the second generalization, which embodied Plücker's correction of his first. Let us consider it for a moment. It is well known that in crystals one constituent can often be substituted for another, without change of external form or internal structure. Iso-morphous crystals are thus rendered

possible. We can replace a diamagnetic atom by a magnetic one, without disturbing the molecular architecture, or the optical phenomena dependent on it. Carbonate of lime, carbonate of lime and iron, and pure carbonate of iron, are cases in point. They are all of the same rhomboidal form; they have the same cleavages which, if followed sufficiently far, would show them to possess the same molecular structure. This identity of structure makes them alike in optical character. They are all three 'negative' crystals. But the atomic change from calcium to iron, which does not affect the optical deportment, completely reverses the magnetic deportment. This single instance suffices to invalidate Plücker's second magnetic classification; while it also disposes of the proposition, so often repeated, that magne-crystallic action is independent of the magnetism or diamagnetism of the mass of the crystal. A host of other exceptions and considerations are, however, adduced.

But a still more fundamental question than that of magne-crystallic action stirred the scientific mind at the period here referred to. The character of the diamagnetic force itself was a subject of doubt and discussion. Was it a polar force, like magnetism, or an unpolar force, like gravity? Diamagnetic repulsion obviously augmented with the strength of the operating magnet. With feeble magnets it was hardly sensible; with strong ones, especially when the more powerful diamagnetic substances like bismuth and antimony were operated on, the repulsion was very sensible indeed. Was this enhancement of the action with the rise of magnetic power due to the magnet alone? Was there no response on the part of the diamagnetic body, like the separation of magnetic fluids in the theory of Poisson, or the arrangement of molecular currents in the theory of Ampère? This portion of the question was answered by Reich, E. Becquerel, and myself, in different ways, but with the same result. It was proved that it was

not the mere *matter* of the diamagnetic body (to which permanence of quantity must be ascribed) that was repelled, but something which, as in the case of magnetism, rose and fell, within wide limits, in exact proportion to the rise and fall of the magnetic power.

The question of diamagnetic polarity, round which the discussion was warmest and most prolonged, comes here into view. After the discovery of diamagnetism, Faraday had thrown out the idea that its phenomena might be explained by assuming in diamagnetic bodies a polarity the reverse of that of magnetic bodies. But he soon abandoned this hypothesis, and never afterwards became reconciled to it. Here, I doubt not, he was swayed, in part, by the results of experiments which he had undertaken in repetition of a series by Professor W. Weber; and, in part, by the sheer unthinkable of either the theory of magnetic fluids, or the theory of molecular currents, as then held, when applied to the fundamental phenomenon of diamagnetic repulsion. It was as a refuge from this difficulty that Professor Weber propounded and developed a theory by which he avoided the contradictions involved in the application to diamagnetism of the theory of Ampère. In iron, according to the latter, the act of magnetization consists in rendering pre-existent currents wholly or partially parallel to a common plane; attraction being due to the fact that the directions of these currents are the same as those of the influencing magnet. In bismuth, according to Weber's theory, the molecular currents are not pre-existent, but *induced*; and, in accordance with Faraday's law, are opposed in direction to the currents which excite them. Hence the repulsion of the bismuth. Ordinary induced currents cease, in a moment, because of the resistance of the conductors through which they pass. Weber, therefore, provides his induced molecular currents with channels of no resistance in which, once started, they can permanently circulate. As justly remarked in a letter

from Professor Weber to myself, this hypothesis of non-resisting circuits is also included in the theory of Ampère. Nobody, of course, who accepts unreservedly this theory, as applied to iron and steel, will find any difficulty in the conception that these channels of perfect conductivity surround atoms which, in their aggregate form, constitute the most powerful insulators. Shell-lac, sulphur, and glass, for example, which are all diamagnetic, must be assemblages of such atoms with their circuits. As a speculation, Weber's theory is beautiful and consistent, and if it affords repose and satisfaction to his powerful mind, it is sure to do the same to the minds of others.

But, being a matter of fact, the question of diamagnetic polarity lies apart from these theoretic considerations. The knowledge that a magnet has two poles does not require to be prefaced by a general theory of magnetism. The essence of magnetic polarity consists in the simultaneous and inseparable existence, or development, of two hostile powers which, in action, always resolve themselves into mechanical couples. Here, it may be said in passing, the key of all Faraday's difficulties—the solution of all the mechanical paradoxes which so perplexed him—is to be found. The facts of magnetic polarity can be mastered and made sure of by anybody possessing a bar magnet and a magnetic needle, or even two magnetic needles. And passing from steel magnets to bars of iron in helices through which electric currents flow, the polarity of the iron is as much a matter of experimental certainty as the polarity of the magnetized steel. The question to be decided was: Do diamagnetic bodies, under magnetic influence, show this doubleness of action? To put the case strongly, iron is repelled by a magnet, as well as attracted; is bismuth attracted by a magnet, as well as repelled? That it is so is abundantly proved in the following pages. Faraday, over and over again, observed this attraction; but it came to him in the disguise of magne-crystallic action, in which,

according to his view, neither attraction nor repulsion had any share.

The subject of diamagnetic polarity was first definitely approached by me in the investigation described in the ‘Third Memoir’ of this series but I had not, at the time, the apparatus and material needed to carry the enquiry out. Thanks to the Council of the Royal Society, this want was soon supplied ; and I faced the investigation recorded in the ‘Fourth Memoir,’ with the resolution to leave no stone unturned in the effort to arrive at the truth. The deportment of diamagnetic bodies was subjected to an exhaustive comparison with that of magnetic bodies, and the antithesis between them, when acted on by all possible combinations of electro-magnets and electric currents, was proved to be absolute and complete. Under the same conditions of excitement the repulsion of the one class of bodies had its complement in the attraction of the other ; the north and south magnetism of the one class had its complement in the south and north magnetism of the other. When the end of an excited iron bar was repelled by a magnetic pole the end of a bismuth bar, under the same influence, was attracted by the same pole ; every deflection, moreover, produced by the combined action of magnets and helices, in the one case, had its exact complement in an opposite deflection in the other. No reasonable doubt, therefore, could rest upon the mind that the diamagnetic force possessed precisely the same claim to the title of a polar force as the magnetic.

This conclusion is further illustrated and enforced by the experiments recorded in the ‘Fifth Memoir.’ These experiments were executed with a most delicate apparatus, expressly devised for me by Professor Weber, of Göttingen, and constructed by Leyser, of Leipzig, with consummate accuracy and skill. With it the various objections which had been urged against Weber’s own results were entirely removed. The severest conditions laid down by the

opponents of diamagnetic polarity were accepted and fulfilled. Conductors and insulators—liquids and solids—were subjected to this new test, and by it also diamagnetic polarity was shown to rest upon as safe a basis as the old and long-recognized magnetic polarity itself.

The argument was rounded off by the application of the doctrine of polarity to magne-crystallic phenomena. This subject is formally approached towards the end of the ‘Fourth Memoir,’ where certain objections which had been urged by Matteucci are examined and removed. In the ‘Sixth Memoir’ the application is carried on. By combining with the doctrine of polarity, the differential attraction and repulsion, first observed in the case of bismuth by Faraday, and extended to other crystals, and to compressed substances, in the ‘Second Memoir’ by myself, all difficulties are caused to disappear; the cases cited by Faraday to prove that *neither* attraction *nor* repulsion was involved in these phenomena being shown to be simple mechanical consequences of the contemporaneous action of *both* attraction *and* repulsion.

I have aimed at rendering this volume small and handy, by omitting various topics which were introduced in the first edition.

J. TYNDALL.

HIND HEAD, HASLEMERE:

April, 1888.

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THE ROYAL INSTITUTION ELECTRO-MAGNET.

(See Frontispiece.)

THE Electro-magnet represented in the Frontispiece is that generally used by Faraday in his researches on Diamagnetism. He employed a retort stand for suspension, covering the poles by a square glass shade, *b c*, to protect the suspended body from currents of air.

The magnet is formed from the link of a great chain-cable ; its section is a distorted square, rounded off at the corners. The magnet, coil inclusive, weighs 272 lbs.

On the ends of the magnet stand two pieces of iron, *P P*, which are the movable poles. They represent those most commonly used by Faraday. Various other poles, however, with rounded, conical, and chisel ends, and some with perforations to allow a beam of light to pass through them, were employed from time to time.

Right and left of the drawing, at *R* and *L*, are shown, in plan, the pole ends, with a little bar in its two characteristic positions, axial and equatorial, between them.

To enable suspended conductors, such as copper cubes or spheres, to rotate in the magnetic field, with the axis of rotation parallel to the lines of force, I had the magnet supported by the pivot *A*, which permits its two arms to be placed, the one above the other, in a horizontal position.

J. T.

FIRST MEMOIR.

THE MAGNETO-OPTIC PROPERTIES OF CRYSTALS AND THE RELATION OF MAGNETISM AND DIA- MAGNETISM TO MOLECULAR ARRANGEMENT.¹

IN the year 1846 our views of magnetic action received, through the researches of Faraday, an extraordinary expansion. The experiments of Brugmans, Le Baillif, Seebeck, and Becquerel had already proved the power to be active beyond the limits usually assigned to it; but these experiments were isolated and limited in number. Faraday was the first to establish the broad fact, that there is no known body indifferent to magnetic influence when the latter is strongly developed. The nature of magnetic action was then found to be twofold, attractive and repulsive; thus dividing bodies into two great classes, which are respectively denominated *magnetic* and *diamagnetic*.

The representative of the former class is *iron*, which, being brought before the single pole of a magnet, is attracted; the representative of the latter class is *bismuth*, which, being brought before the single pole of a magnet, is repelled.²

If a little bar of iron be hung freely between the two poles of a magnet, it will set its longest dimension in the

¹ Published jointly with Professor Knoblauch in the Philosophical Magazine, July 1850.

² Faraday afterwards suggested that the general term *magnetism* should include both the magnetism of iron and that of bismuth, which he respectively designated *paramagnetism* and *diamagnetism*.

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line joining the poles; a little bar of bismuth, on the contrary, will set its longest dimension at right angles to the line joining the poles.

The position of the iron is termed by Faraday the *axial* position, that of the bismuth the *equatorial* position. We shall have occasion to use these terms.

These discoveries, opening, as they did, a new field in physical science, invited the labours of scientific men on the Continent. Weber, Ørsted, Reich, and others have occupied themselves with the subject. But, if we except the illustrious discoverer himself, there is no investigator in this branch of science whose labours have been so richly rewarded as those of Professor Plücker of Bonn.

In 1847 Plücker had a magnet constructed of the same size and power as that described by Faraday,¹ his object being to investigate the influence of the fibrous constitution of plants upon their magnetic deportment. While conducting these experiments, he was induced to try whether crystalline structure exercised an influence. ‘The first experiment,’ says Plücker, ‘gave an immediate and decided reply.’

Following up his investigations with crystals, he was led to the affirmation of the following two laws :—

‘When any crystal whatever with one optic axis is brought between the poles of a magnet, the axis is repelled by each of the poles; and if the crystal possess two axes, each of these is repelled, with the same force, by the two poles.

‘The force which causes this repulsion is independent of the magnetism or diamagnetism of the mass of the crystal; it decreases with the distance more slowly than the magnetic influence exerted by the poles.’²

It is, perhaps, worth explaining that if, on exciting the

¹ Phil. Mag., vol. xxviii. p. 396.

² Poggendorff's Annalen, vol. lxxii. p. 75.

magnet, the optic axis take up the *axial* position, it is said to be attracted; if the *equatorial*, it is said to be repelled.

The first experiment of Plücker, which led to the affirmation of these laws, was made with tourmaline. A plate of the crystal which had been prepared for the purposes of polarisation, twelve millimetres long, nine wide, and three thick, was suspended by a silk fibre between the poles of an electro-magnet. On sending a current round the latter, the plate, which was magnetic, set itself as an ordinary magnetic substance would do, with its longest dimension from pole to pole. The optic axis of the crystal, thus suspended, was vertical.

On hanging the crystal, however, with its optic axis horizontal, when the magnet was excited, the plate stood no longer as a magnetic substance, but as a diamagnetic; its longest dimension being at right angles to the line joining the poles. The optic axis of the crystal was found to coincide with its length, and the peculiar deportment was considered as a proof that the optic axis was repelled.

This law was further established by experiments with Iceland spar, quartz, zircon, beryl, &c., and, as above stated, included crystals of all kinds, both optic positive and negative. It has, however, lately undergone considerable modification at the hands of Plücker himself. In a letter to Faraday, which appears at page 450, vol. xxxiv. of the 'Philosophical Magazine,' he expresses himself as follows:—

'The first and general law I deduced from my last experiments is the following:—"There will be *either repulsion or attraction* of the optic axes by the poles of a magnet, according to the crystalline structure of the crystal. If the crystal is a *negative* one, there will be *repulsion*; if it is a *positive* one, there will be *attraction*."¹

¹ Phil. Mag., vol. xxxiv. p. 450.

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This law applies to crystals possessing two optic axes, each of the said axes being attracted or repelled according as the crystal is positive or negative. It will simplify the subject if we regard the line bisecting the acute angle enclosed by the two axes as the resultant of attraction or repulsion ; for the sake of convenience, we shall call this the *middle line*. In positive crystals, therefore, the middle line, according to the above law, must stand *axial* ; in negative crystals, *equatorial*. It is also evident that the plane passing through the optic axes must, in the one class of crystals, stand from pole to pole, in the other class at right angles to the line joining the poles.

In explaining this new modification of the law, Plücker lays particular emphasis upon the fact that the attraction or repulsion is the result of an independent force, connected in no way with the magnetism or diamagnetism of the mass of the crystal ; and this view is shared by Faraday, who, in expressing his concurrence with Plücker, denominates the force in question an ‘optic axis force.’¹

The experiments described in our first paper upon this subject² furnish, we conceive, sufficient ground of dissent from these views. In the case of five crystals of pure carbonate of lime (Iceland spar), we found the law of Plücker strictly verified, all five crystals being diamagnetic ; on replacing, however, a portion of the carbonate of lime by carbonate of iron, nature herself being the chemist in this case, the crystal was no longer diamagnetic, but magnetic ; in every other respect it was physically unchanged ; its optical properties remained precisely as before, the crystal of carbonate of lime and the crystal of carbonate of lime and iron being both negative. In the

¹ Phil. Trans., 1849, p. 32.

² Phil. Mag., vol. xxxvi. p. 178. A short preliminary notice printed further on.

one case, however, the optic axis was attracted; in the other the said axis was repelled, the attraction being evidently caused by the passage of the crystal from the diamagnetic into the magnetic state.

We have examined other crystals of the same form as Iceland spar, both magnetic and diamagnetic. In all cases the former act in a manner precisely similar to the carbonate of lime and iron already described, while the latter behave as the pure carbonate of lime. The following are examples:—

Nitrate of Soda.—This crystal is of the same form as carbonate of lime, and, like it, diamagnetic. Its deportment is in every respect the same. A rhombus cloven from the crystal and suspended horizontally between the poles sets its longer diagonal axial. Suspending the full crystal between the poles, with its optic axis horizontal, on exciting the magnet this axis sets itself equatorial.

Breunnerite.—This is a crystal composed principally of carbonate of lime and carbonate of magnesia, but containing a sufficient quantity of the carbonate of iron to render it magnetic. Suspended in the magnetic field, the optic axis sets from pole to pole.

Dolomite.—In this crystal a portion of the lime is replaced by protoxide of iron and protoxide of manganese, which ingredients render it magnetic. The optic axis sets from pole to pole.

Carbonate of Iron.—In the cases just cited, the substitution of iron for calcium was partial; in the case now before us the substitution is complete. This crystal differs in nothing, save in the energy of its action, from the magnetic crystals already described. If a full crystal be hung between the poles, with its optic axis horizontal, on sending a current round the magnet the axis sets strongly in the line joining the poles, vibrates through it quickly for a time, and finally comes to rest.

6 DIAMAGNETISM AND MAGNE-CRYSTALLIC ACTION.

there. If a thin rhombus be cloven from the crystal and suspended from one of its obtuse angles with its parallel faces vertical, it will set itself exactly equatorial. In this case it is easy to see that the horizontal projection of the optic axis, which passes through the obtuse angle of the crystal, stands axial. Hung from its acute angle, the rhombus takes up an oblique position, making a constant angle with the line joining the poles. To this position, if forcibly removed from it, it will invariably return. The position may be either right or left of the axial line; but the angle of obliquity is always the same, being the angle which the optic axis makes with the face of the rhombus. Hung from the obtuse angle the obliquity is nothing—from the acute angle it is a maximum; the rhombus is capable of all degrees of obliquity between these extremes, *the optic axis setting in all cases from pole to pole.*

Oxide of Iron.—The above phenomena are exhibited even in a more striking manner by this crystal. So strong is the directive power that a rhombus, suspended from one of its obtuse angles, will set itself strongly equatorial, though its length may be fifteen or twenty times its breadth.

What is the conclusion to be drawn from these experiments? We have first of all a diamagnetic crystal of pure carbonate of lime, which sets its optic axis equatorial. On substituting for a portion of the lime a quantity of protoxide of iron sufficient to render the crystal weakly magnetic, we find the axis attracted instead of repelled. Replacing a still further quantity of the diamagnetic lime by a magnetic constituent, we find the attraction stronger, the force with which the optic axis takes up the axial position increasing as the magnetic constituents increase. These experiments appear to be irreconcilable with the statement, that the position of the optic axis is independent

of the magnetism or diamagnetism of the mass of the crystal.

Turning now to crystals possessing two optic axes, we find the law of Plücker equally untenable.

Dichroite.—This crystal, as is well known, receives its name from its ability to transmit light of two different colours. The specimen examined by us is a cube. In the direction of the '*crystallographic*' axis, which coincides with the '*middle line*,' the light transmitted is yellowish; through the other four sides of the cube it is a deep blue. Suspended with the middle line horizontal, whatever be the position of that line before closing the circuit, the instant the magnetic force is developed it turns with surprising energy into the axial position and becomes fixed there. According to the law, however, the middle line should stand equatorial, for the crystal is negative.¹

Sulphate of Baryta (Heavy spar).—The form of this crystal is a prism whose base is a rhombus, the four sides being perpendicular to the base. It cleaves parallel to the sides and base. Suspended between the poles, with the axis of the prism vertical, on exciting the magnet, though the crystal is diamagnetic, the long diagonal sets itself axial. It agrees thus far with the carbonate of lime. Suspended from the acute angle formed by two sides of the prism, on closing the circuit the axis sets parallel to the line joining the poles, and remains there as long as the force is active. Suspending the crystal from its obtuse angle, the axis being still horizontal, on closing the circuit the axis sets itself equatorial. A plane perpendicular to the rhombic base, and passing through the long diagonal, contains the two optic axes, which are inclined to each other at an angle of 38°. The middle line bisecting this angle is parallel to the axis of the prism, and hence stands axial or equatorial, according as the prism is suspended

¹ Brewster's list.

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from its acute or its obtuse angle. The position of the middle line is therefore a function of the point of suspension, varying as it varies; at one time supporting the law of Plücker, and at another time contradicting it. Heavy spar is positive.

Sulphate of Strontia (Cœlestine).—This is also a positive crystal, its form being precisely that of heavy spar; the only difference is this, that, in Cœlestine, the optic axes enclose an angle of 50° instead of 38° . The corroboration and contradiction exhibited by heavy spar are exhibited here also.

Sulphate of Zinc.—Suppose the crystalline prism to be hung from its end, and the line which stands equatorial when the magnet is excited carefully marked. A plate taken from the crystal, parallel to this line and to the axis of the prism, displays, on examination with polarised light, the ring systems surrounding the ends of the two optic axes. The middle line which bisects the acute angle enclosed by these axes, is perpendicular to the surface of the plate, and therefore stands axial. It ought, however, to stand equatorial, for the crystal is negative.

Sulphate of Magnesia.—Suspending the crystalline prism from its end, and following the method applied in the case of sulphate of zinc, we discover the ring systems and the position of the middle line. This line stands axial; the crystal is nevertheless negative.

Topaz.—This being one of the crystals pronounced by Plücker as peculiarly suited to the illustration of his new law, it is perhaps on that account deserving of more than ordinary attention. In the letter to Faraday, before alluded to, he writes:—

‘The crystals most fitted to give evidence of this law are *diopside* (a positive crystal), *cyanite*, *topaz* (both negative), and others crystallising in a similar way. In

these crystals the line (*A*), bisecting the acute angles made by the two optic axes, is neither perpendicular nor parallel to the axis (*B*) of the prism. Such a prism, suspended horizontally, will point neither axially nor equatorially, but will take always a fixed intermediate direction. This direction will continually change if the prism be turned round its own axis (*B*). It may be proved by a simple geometrical construction, which shows that during one revolution of the prism round its axis (*B*), this axis, without passing out of two fixed limits *c* and *d*, will go through all intermediate positions. The directions *c* and *d*, where the crystal returns, make, *either* with the line joining the two poles, *or* with the line perpendicular to it, on both sides of these lines, angles equal to the angle included by *A* and *B*; the first being the case if the crystal be a *positive* one, the last if a *negative* one. Thence it follows that if the crystal, by any kind of horizontal suspension, should point to the poles of a magnet, it is a *positive* one; if it should point equatorially, it is a *negative* one.¹

In experimenting with this crystal, we have found the greatest care to be necessary. Its diamagnetic force is so weak, that the slightest local impurity, contracted by handling or otherwise, is sufficient to derange its action. The crystals as they come from the mineralogist are unfit for exact experiment. We have found it necessary to boil those we have used in muriatic acid, and to scour them afterwards with fine white sand, reduced to powder in a mortar. These precautions taken, we have been unable to obtain the results described by Plücker. We have examined five specimens of topaz from Saxony, the axial dimension of some of them exceeding the dimension perpendicular thereto by one-half; the axis, notwithstanding, stands in all cases from pole to pole. Two specimens of Brazilian topaz, the one of an amber colour, the other almost

¹ Phil. Mag., vol. xxxiv. p. 450.

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as clear as distilled water, gave the same results ; the axes of the crystals stand from pole to pole, and turning round makes no difference. On a first examination, some of the crystals exhibited an action similar to that described by Plücker ; but after boiling and scouring, these irregularities disappeared, and the axes one and all stood axial.

One crystal in particular caused us considerable embarrassment. Its action was irregular, and the irregularity remained after the adoption of the methods described to ensure purity. On examination, however, a splinter from one of its sides was found to be attracted, a splinter from the side opposite was found to be repelled. To the naked eye the crystal appeared clean and clear. On examination, however, under a powerful microscope, the side of the crystal from which the magnetic splinter was taken was found dotted with small black particles imbedded in its mass ; the other side of the crystal was perfectly transparent. On cleaving away the impurities, the irregularity vanished, and the crystal stood as the others.

In the letter quoted, diopside is pronounced to be a positive crystal. On examination with circular polarized light, as recommended by Dove,¹ we find the crystal to be negative. The same method pronounces topaz positive, instead of negative, as affirmed by Plücker. The specimens we have examined in this way are from Brazil and Saxony. Aberdeen topaz we have not examined, but it also is classed by Brewster among positive crystals. The obliquity of the middle line of topaz does not exist in the specimens which have come under our notice ; it is exactly perpendicular to the planes of principal cleavage, and consequently exactly parallel to the axis of the prism. This agrees with the results of

¹ Poggendorff's *Annalen*, vol. xl. pp. 457, 482.

Brewster, who found the optic axes to be ‘equally inclined to the plain of cleavage.’¹

In experimenting with weak diamagnetic crystals, the greater the number of examples tested the better; as, if local impurity be present, it is thus more liable to detection. Our results with heavy spar have been confirmed by ten different crystals; with cœlestine, by five; and with topaz, as has been stated, by seven. The suspending fibre, in these and similar instances, was a foot in length and $\frac{1}{2500}$ of an inch thick, or about one-eighth of the diameter of a human hair.

Sugar.—It is well known that this crystal forms a prism with six sides, two of which are generally very prominent, the principal cleavage being parallel to these two, and to the wedge-like edge which runs along the end of the prism. The plane of the optic axes is perpendicular to the axis of the prism, and their ends may be found by cutting out a plate parallel to that axis, and inclined to the principal cleavage at an angle of about 20° . Such a plate exhibits both ring systems symmetrically, while a plate parallel to the principal cleavage exhibits one system only. Suspended between the excited poles, with the axis of the prism horizontal, and the principal cleavage vertical, the plane of the optic axes sets axial. According to the law of Plücker, it ought to stand equatorial, for the crystal is negative.

Rock-crystal (Quartz).—This crystal has undergone more than one examination by the learned German, its deportment being, ‘contrary to all expectation,’ very weak—a result, it may be remarked, difficult of explanation on the hypothesis of an ‘optic axis force.’ Plücker’s first experiments with this crystal were apparently made with great exactitude, the crystal being reduced to a spherical shape, and the influence of mere form thus annulled. These

¹ Lardner’s Encyclopædia, Optics, p. 204.

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experiments proved the optic axis to be repelled. Later researches, however, induced the philosopher to alter his opinion, and accordingly, in his last memoir,¹ we find quartz ranked with those crystals whose optic axes are attracted, with the remark ‘weak’ added parenthetically. We have not been able to obtain this deportment. After the washing and scouring process, the finest and most transparent crystals we could procure confirmed the first experiments of Plücker, and therefore contradict the new modification of his law. It is almost incredible how slight an impurity is sufficient to disturb the action of this crystal. A specimen with smaller crystals attached to it, or growing through it, is suspicious and ought to be rejected. Clear isolated crystals are alone suitable. We must remark that a fine cube, with faces half an inch square, suspended with the optic axis horizontal, showed no directive action; either one or the other of the diagonals set itself from pole to pole, though the axis ran parallel to four of the faces.

As far as it has been practicable, we have ourselves cut, cloven, and examined the optical properties of the crystals which have passed through our hands, testing, in every possible case, the results of others by actual experiment. Most of the crystals in Brewster’s list have been gone through in this way. Iceland spar, quartz, mica, arragonite, diopside, lepidolite, topaz, saltpetre, sugar, sulphate of zinc, sulphate of magnesia, and others have been examined and verified. In two cases, however, our results differed from the list, these being sulphate of nickel and borax. A prism of sulphate of nickel was suspended from its end between the poles; on exciting the magnet it took up a determinate position. When it came to rest, a line parallel to the magnetic axis was marked thereon, and a plate taken from the crystal parallel

¹ Poggendorff’s *Annalen*, vol. lxxviii. p. 428.

to this line and to the axis of the prism. Such a plate, ground thin, exhibited in the polariscope a pair of very beautiful ring systems. The ring systems of borax were found in a similar manner. The middle line, therefore, in both cases stood equatorial, and, according to the list, would contradict the law of Plücker, for both are there set down as *positive*. A careful examination with circular polarised light led us to the opposite conclusion. We thought it worth while to send specimens of each to Berlin, so as to have them examined by Professor Dove, the author of the method by which we examined them. The crystals have been returned to us with a note certifying that they are *negative*, thus confirming our observations.

Yellow Ferrocyanide of Potassium.—This crystal does not stand in the list of Brewster, and we have sought for it in other lists in vain. In one German work on physics we find *Blutlaugensalz* set down as a negative crystal with one optic axis, but whether the red or yellow salt is meant, the author does not explain. We have examined the crystal ourselves, and find it positive with two optic axes. The middle line stands perpendicular to the principal cleavage. Suspended with this line horizontal, on closing the circuit it sets itself equatorial. Another exception to the law under consideration is here exhibited.

Plücker recommends the magnet as a practical means of determining whether a crystal is positive or negative; this method being attended with the peculiar advantage that it can be applied in the case of opaque crystals, where all the ordinary methods fail. We find accordingly, in his last memoir on this subject, that metallic and other opaque crystals have optical properties attributed to them. Antimony is negative with one optic axis; bismuth and arsenic are positive with one

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optic axis. The foregoing experiments demonstrate the insecurity of the basis on which this classification rests.

By looking back upon the results described, it will be seen that we have drawn from each respective class of crystals one or more examples which disobey the law of Plücker. Of positive crystals with one axis, we have quartz; of positive crystals with two axes, we have heavy spar, coelestine and ferrocyanide of potassium. Of negative crystals with one axis, we have carbonate of lime and iron, and several others; of negative crystals with two axes, we have dichroite, sugar, sulphate of zinc, and sulphate of magnesia. It is but just, however, to state that, in a considerable number of cases, we have found the law confirmed. Tourmaline, idocrase, beryl, Iceland spar, saltpetre, arragonite, and many others, all confirm it. Singularly enough, these are the very crystals with which Plücker has experimented. It is therefore not to be wondered at, that he should be led by such a mass of concurring evidence to pronounce his law general. Had his experiments embraced a sufficient number of cases, they would doubtless have led him to the same conclusion to which ours have conducted us.

Faraday has devoted considerable time to the investigation of this intricate subject. His most notable experiments are those with *bismuth*, *antimony*, *arsenic*, *sulphate of iron*, and *sulphate of nickel*, which experiments we have carefully repeated.

Bismuth.—Crystals of bismuth we have ourselves prepared, by melting the metal in a Hessian crucible, placed within a larger one and surrounded by fine sand. In this state it was allowed to cool slowly, until a thin crust gathered on the surface. At this point the crust was pierced, and the molten metal underneath poured out, thus leaving the complete crystals clustering round

the sides and bottom. Our experiments with these crystals corroborate, to the letter, those so minutely described by Faraday in the Bakerian Lecture, delivered before the Royal Society in 1849.¹

Arsenic.—Our arsenic we procured at the druggists'. It is well known that this metal is usually obtained by the sublimation of its ore, the vapour being condensed in suitable receivers, where it is deposited in a crystalline form. There is a difference of opinion between Faraday and Plücker as regards this metal; the former holding it for diamagnetic, the latter for magnetic. Several specimens, obtained from different druggists, corroborated the view of Plücker. They were all *magnetic*.

About half an ounce of the metal was introduced into a glass tube, closed at one end and open at the other. About five inches of the tube, near the open end, was crammed full of copper turnings, and the open end introduced through a small aperture into the strong draft of a flue from a heated oven. The portion of the tube containing the copper turnings was heated to redness, and by degrees the oxygen within the tube was absorbed. The arsenic at the other end was then heated and sublimed. After some time the vapour was allowed to condense slowly, and a metallic deposit was the consequence—the arsenic thus obtained was *diamagnetic*. The deportment of the crystal is described by Faraday in the place above referred to.

Antimony.—A difference of opinion exists with regard to the action of this crystal also. Referring to the deportment assigned to it by Faraday, Plücker writes, ‘to my astonishment, however, antimony behaved in a manner directly the reverse. While on the one side a prism of bismuth, whose principal cleavage coincided with the base of the prism, set itself *axial*; and on the other

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side a plate of arsenic, which, on account of its magnetism, ought to stand *axial*, set itself *equatorial*; a plate of antimony deviated completely from this deportment, and although the mass was strongly diamagnetic, set itself decidedly *axial*.'

Plücker's results differ from those of Faraday in two particulars: first, a plate of antimony, similar to that described by the German philosopher, is found by Faraday to stand *equatorial* instead of *axial*; secondly, the following phenomena, observed by Faraday, appear not to have exhibited themselves in Plücker's experiments:—‘On the development of the magnetic force, the crystal went up to its position slowly, and pointed as with a dead set. Other crystals did the same imperfectly; and others again made one or perhaps two vibrations, but all appeared as if they were moving in a thick fluid, and were, in that respect, utterly unlike bismuth, in the freedom and mobility with which it vibrated. If the crystalline mass was revolving when the magnetic force was excited, it suddenly stopped, and was caught in a position which might, as was found by experience, be any position. The arrest was followed by a revulsive action on the discontinuance of the electric current.’¹

In most of the specimens examined by us these phenomena were also absent, and the results of Plücker presented themselves. Three specimens, however, behaved exactly in the manner described by Faraday, exhibiting a singular inertness when the magnetic force was present, and a revulsion from the poles on breaking the circuit. To ascertain, if possible, the cause of this difference, we dissolved an example of each class in muriatic acid, precipitated the antimony with distilled water, and

¹ Phil. Trans., 1849, p. 14. For an explanation see Phil. Mag., vol. xxviii. p. 460.

tested the clear filtrate with ferrocyanide of potassium. The specimen which agreed with Plücker exhibited a faint bluish tint, characteristic of the presence of iron; that which corroborated Faraday showed not the slightest trace of this metal. The iron, though thus revealing itself, must have been present in a quantity exceedingly minute, for the antimony was diamagnetic. Whether this has been the cause of the difference between the two philosophers we will not undertake to say; irregular crystalline structure may also have had an influence.

We have here a crowd of examples of crystalline action in the magnetic field, but as yet not a word of explanation. Plücker's hypothesis has evidently failed. We now turn to the observations of Faraday, and shall endeavour to exhibit, in the briefest manner possible, the views of this profound investigator.

After a general description of the action of bismuth between the poles, Faraday writes:—‘The results are, altogether, very different from those produced by diamagnetic action. They are equally distinct from those dependent on ordinary magnetic action. They are also distinct from those discovered and described by Plücker, in his beautiful researches into the relation of the optic axis to magnetic action; for there the force is equatorial, whereas here it is axial. So they appear to present to us a new force, or a new form of force in the molecules of matter, which, for convenience' sake, I will conventionally designate by a new word, as the *magne-crystallic* force.’¹

‘The magne-crystallic force appears to be very clearly distinguished from either the magnetic or diamagnetic forces, in that it causes neither approach nor recession; consisting not in attraction or repulsion, but in its giving a certain determinate position to the mass under its influence, so that a given line in relation to the mass is

¹ Phil. Trans., 1849, p. 4.

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brought by it into a given relation with the direction of the external magnetic power.'¹

The line through the crystal which sets itself with greatest force from pole to pole, is termed by Faraday the magne-crystallic axis of the crystal. He proves by experiment that bismuth has exactly the same amount of repulsion whether this axis be *parallel* or *transverse* to the lines of magnetic force acting on it.²

'In other experiments a vertical axis was constructed of cocoon silk, and the body to be examined was attached to it at right angles as radius; a prismatic crystal of sulphate of iron, for instance, whose length was four times its breadth, was fixed on the axis with its length as radius and its magne-crystallic axis horizontal, and therefore as tangent; then, when this crystal was at rest under the torsion force of the silken axis, an electro-magnetic pole was so placed that the axial line of magnetic force should be, when exerted, oblique to both the length and the magne-crystallic axis of the crystal; and the consequence was, that, when the electric current circulated round the magnet, the crystal actually *receded* from the magnet under the influence of the force, which tended to place the magne-crystallic axis and the magnetic axis parallel. Employing a crystal or plate of bismuth, that body could be made to *approach* the magnetic pole under the influence of the magne-crystallic force; and this force is so strong as to counteract either the tendency of the magnetic body to approach, or of the diamagnetic body to retreat, when it is exerted in the contrary direction.' Hence Faraday concludes that it is neither attraction nor repulsion which causes the set or determines the final position of a magne-crystallic body.³

¹ Phil. Trans., 1849, p. 22.'

² Faraday afterwards corrected this.

Phil. Mag., vol. xxxiv. p. 77.

'As made manifest by the phenomena, the magne-crystallic force is a force acting at a distance, for the crystal is moved by the magnet at a distance, and the crystal can also move the magnet at a distance.' Faraday obtained the latter result by converting a steel bodkin into a magnet, and suspending it freely in the neighbourhood of the crystal. The tendency of the needle was always to place itself parallel to the magne-crystallic axis.

Crystals of bismuth lost their power of pointing at the moment the metal began to fuse into drops over a spirit-lamp or in an oil-bath. 'Crystals of antimony lost their magne-crystallic power below a dull red heat, and just as they were softening so as to take the impression of the copper loop in which they were hung.' Iceland spar and tourmaline, on the contrary, on being raised to the highest temperature which a spirit-lamp could give, underwent no diminution of force; they pointed equally well as before.

Faraday finally divides the forces belonging to crystals into two classes—*inherent* and *induced*. An example of the former is the force by which a crystal modifies a ray of light which passes through its mass; the second is developed exclusively by magnetic power. To this latter, as distinct from the other, Faraday has given the name *magneto-crystallic*. To account for crystalline action in the magnetic field, we have, therefore, the existence of *three new forces* assumed:—the *optic axis* force, the *magne-crystallic* force, and the *magneto-crystallic* force.

With regard to the experimental portion of Faraday's labours on this subject, we have only to express our admiration of the perfect exactitude with which the results are given. It appears to us, however, a matter of exceeding difficulty to obtain a clear notion of any such force

as he has described ; that is to say, a force proceeding from the pole of a magnet, and capable of producing such motions in the magnetic field, and yet neither attractive nor repulsive.

That a crystal of bismuth should approach the magnetic pole, and that a crystal of sulphate of iron should recede therefrom, appears, at first sight, anomalous, but certainly not more so than other phenomena connected with one of Faraday's most celebrated discoveries, and explained in a beautiful and satisfactory manner by himself.

If we hang a penny from its edge in the magnetic field, and so arrange the suspending thread that the coin, before the magnetic power is developed, shall make an angle of 45° , or thereabouts, with the line joining the poles ; then, on closing the circuit, and sending a current round the magnet, the coin will suddenly turn, as if it made an effort to set itself from pole to pole ; and if its position beforehand be nearly axial, this effort will be sufficient to set it *exactly* so ; the penny thus behaving, to all appearance, as if it were attracted by the poles.

The real cause of this, however, is *repulsion*. During the development of magnetic power, an electric current is aroused in the copper coin, which circulates round the coin in a direction opposite to that of the current which passes from the battery round the coils of the magnet. The effect of this induced current is to create a polar axis in the copper ; and when the direction of the current is considered, it is easy to see that the north end of this axis must *face* the north pole of the magnet, and will consequently be repelled. On looking therefore at the penny, apparently attracted as above described, we must, if we would conceive rightly of the matter, withdraw our attention from the coin itself, and fix it on a line passing through its centre, and at right angles

to its flat surface; this is the polar axis of the penny, the repulsion of which causes the apparent attraction.

We do not mean to say that any such action as that here described takes place with a bismuth crystal in the magnetic field. The case is cited merely to show that the ‘approach’ of the bismuth crystal, noticed by Faraday, *may* be really due to *repulsion*; and the ‘recession’ of the sulphate of iron really due to *attraction*.

Our meaning will perhaps unfold itself more clearly as we proceed. If we take a slice of apple, about the same size as the penny, but somewhat thicker, and pierce it through with short bits of iron wire, in a direction perpendicular to its flat surface, such a disc, suspended in the magnetic field, will, on the evolution of the magnetic force, recede from the poles and set its horizontal diameter strongly equatorial; *not* by repulsion, but by the attraction of the iron wires passing through it. If, instead of iron, we use bismuth wire, the disc, on exciting the magnet, will turn into the axial position; *not* by attraction, but by the repulsion of the bismuth wires passing through it.

If we suppose the slice of apple to be replaced by a little cake made of a mixture of flour and iron filings, the bits of wire running through this will assert their predominance as before; for though the whole is strongly magnetic, the superior energy of action along the wire will determine the position of the mass. If the bismuth wire, instead of piercing the apple, pierce a little cake made of flour and bismuth filings, the cake will stand between the poles as the apple stood; for though the whole is diamagnetic, the stronger action along the wire will be the ruling agency as regards position.

Is it not possible to conceive an arrangement among the molecules of a magnetic or diamagnetic crystal, capable of producing a visible result similar to that here described?

If, for example, in a magnetic or diamagnetic mass, two directions exist, in one of which the contact of the particles is closer than in the other, may we not fairly conclude that the strongest exhibition of force will be in the former line, which therefore will signalise itself between the poles, in a manner similar to the bismuth or iron wire? If analogic proof be of any value, we have it here of the very strongest description. For example:—bismuth is a brittle metal, and can readily be reduced to a fine powder in a mortar. Let a teaspoonful of the powdered metal be wetted with gum-water, kneaded into a paste, and made into a little roll, say an inch long and a quarter of an inch across. Hung between the excited poles, it will set itself like a little bar of bismuth—equatorial. Place the roll, protected by bits of pasteboard, within the jaws of a vice, squeeze it flat, and suspend the plate thus formed between the poles. On exciting the magnet the plate will turn, with the energy of a magnetic substance, into the axial position, though its length may be ten times its breadth.

Pound a piece of carbonate of iron into fine powder, and form it into a roll in the manner described. Hung between the excited poles, it will set as an ordinary magnetic substance—axial. Squeeze it in the vice and suspend it edgeways, its position will be immediately reversed. On the development of the magnetic force, the plate thus formed will recoil from the poles, *as if violently repelled*, and take up the equatorial position.

We have here ‘approach’ and ‘recession,’ but the cause is evident. The line of closest contact is perpendicular in each case to the surface of the plate—a consequence of the pressure which the particles have undergone in this direction; and this perpendicular sets axial or equatorial according as the plate is magnetic or diamagnetic. We have here a ‘directive force,’ but it is attraction

or repulsion modified. May not that which has been here effected by artificial means occur naturally? Must it not actually occur in most instances? for, where perfect homogeneity of mass does not exist, there will always be a preference shown by the forces for some particular direction. This election of a certain line is therefore the rule and not the exception. It will assist both the reader and us if we give this line a name; we therefore propose to call it *the line of elective polarity*.¹ In magnetic bodies this line will set axial, in diamagnetic equatorial.

'The relation of the magne-crystallic force,' says Faraday, 'to the magnetic field is axial and not equatorial.' This he considers to be proved by the following considerations:—Suppose a crystal of bismuth so suspended that it sets with its *maximum* degree of force, then if the point of suspension be moved 90° in the axial plane, so that the line which in the last case stood horizontal and axial, may now hang vertical, then the action is a *minimum*: now, contends Faraday, if the force were equatorial this change in the axial plane ought not to have affected it; that is to say, if the force act at right angles to the axial plane, it is all the same which point of the plane is chosen as the point of suspension.

This seems a fair conclusion; but the other is just as fair—that, if the force be axial, a change of the point of suspension in the equatorial plane cannot disturb it. In sulphate of nickel, Faraday finds the line of maximum force to be parallel to the axis of the prism. Whatever, therefore, be the point of suspension in the plane perpendicular to the axis, the action ought to be the same. On examining this crystal it will probably be found that two

¹ The principal axis of magnetic induction.—J. T. 1870.

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opposite corners of the parallelopiped are a little flattened. Let the prism be hung with its axis horizontal and this flattening vertical, and after the evolution of the magnetic force let the oscillations of the prism be counted. Move the point of suspension 90° in the equatorial plane, so that the flattening shall be horizontal, and again count the oscillations. The numbers expressing the oscillations in the two cases will be very different. The former will be a *maximum*, the latter a *minimum*. But if the force be axial this is impossible, therefore the force is not axial.

Whatever be the degree of conclusiveness which attaches itself to the reasoning of Faraday drawn from bismuth; precisely the same degree attaches to the reasoning drawn from sulphate of nickel. The conclusions are equal and opposite, and hence destroy each other. It will probably be found that the reasoning in both cases is entirely correct; that the force is neither axial nor equatorial, in the sense in which these terms are used.

A number of thin plates, each about half an inch square, were cut from almond kernels, with an ivory blade, parallel to the cleft which divides the kernel into two lobes. These were laid one upon the other, with strong gum between them, until a cube was obtained. A few minutes in the sunshine sufficed to render the cube dry enough for experiment. Hung between the poles, with the line perpendicular to the layers horizontal, on exciting the magnet this line turned and set itself parallel to the magnetic resultant passing through the mass. The action here was a *maximum*. Turning the cube round 90° in the axial plane, there was scarcely any directive action. If the word 'crystal' be substituted for 'cube' in the description of this deportment, every syllable of it is applicable to the case of bismuth; and if the deportment of the crystal warrant the conclusion that the force

is axial, the deportment of the cube warrants the same conclusion. *Is the force axial in the case of the cube? Is the position of the line perpendicular to its layers due to the 'tendency' of that line to set itself parallel to the magnetic resultant?* The kernel is strongly diamagnetic, and the position of the perpendicular is evidently a secondary result, brought about by the repulsion of the layers. *Is it not then possible, that the approach of the magne-crystallic axis, in bismuth, to the magnetic resultant, is really due to the repulsion of the planes of cleavage?*

But here the experiment with the silken axis meets us; which showed that, so far from attraction being the cause of action in a magnetic crystal, there was actual *recession*; and so far from repulsion being the cause in a diamagnetic crystal, there was actual *approach*. This objection it is our duty to answer.

A model was constructed of powdered carbonate of iron, about 0·3 of an inch long and 0·1 in thickness, and, by attention to compression, it was arranged that the line of elective polarity through the model was perpendicular to its length. Hanging a weight from one end of a fibre of cocoon silk a vertical axis was obtained; a bit of card was then slit and fitted on to the axis, so that when the model was laid on one side, the card stood like a little horizontal table in the middle of the magnetic field. The length of the model extended from the central axis to the edge of the card, so that when the mass swung round, its line of elective polarity was tangent to the circle described.

When the model was made to stand between the flat-faced poles obliquely, the moment the magnet was excited it moved, tending to set its length equatorial and its line of elective polarity parallel to the lines of magnetic force. In this experiment the model of carbonate of iron, though

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a magnetic body and strongly attracted by such a magnet as that used, actually *receded* from the magnetic pole.

If, instead of the model of carbonate of iron, we substitute a crystal of sulphate of iron, we have the experiment instituted by Faraday to prove the absence of attraction or repulsion. The dimensions are his dimensions, the arrangement is his arrangement, and the deportment is the exact deportment which he has observed. We have copied his very words, these words being perfectly descriptive of the action of the model. If, then, the experiment be 'a striking proof that the effect is not due to attraction or repulsion' in the one case, it must also be such in the other case; but the great experimenter will, we imagine, hardly push his principles so far. He will, we doubt not, be ready to admit, that it is more probable that a line of elective polarity exists in the crystal, than that a magne-crystallic axis exists in the model.¹

By a similar proceeding, using bismuth powder instead of carbonate of iron, the action of Faraday's plate of bismuth may be exactly imitated. The objection to the conclusion, that the approach of the magne-crystallic axis, in bismuth, to the magnetic resultant, is due to the repulsion of the planes of cleavage, is thus, we conceive, fairly met.

Let us look a little further into the nature of this magne-crystallic force, which, as is stated, is neither attraction nor repulsion, but gives position only. The magne-crystallic axis, says Faraday, *tends* to place itself parallel to the magnetic resultant passing through the crystal; and in the case of a bismuth plate, the recession from the pole and the taking up of the equatorial position is not due to repulsion, but to the *endeavour* of the

¹ The term magne-crystallic axis may with propriety be retained, even should our views prove correct; but then it must be regarded as a subdenomination of the line of elective polarity.

bismuth to establish the parallelism before mentioned. Leaving attraction and repulsion out of the question, we find it extremely difficult to affix a definite meaning to the words 'tends' and 'endeavour.' 'The force is due,' says Faraday, 'to that power of the particles which makes them cohere in regular order, and gives the mass its crystalline aggregation, which we call at times the attraction of aggregation, and so often speak of as acting at insensible distances.' We are not sure that we fully grasp the meaning of the philosopher in the present instance; for the difficulty of supposing that what is here called the attraction of aggregation, considered apart from magnetic attraction or repulsion, can possibly cause the rotation of the *entire mass* round an axis, and the taking up of a fixed position by the mass, with regard to surrounding objects, appears to us insurmountable. We have endeavoured to illustrate the matter, to our own minds, by the action of a piece of leather brought near a red-hot coal. The leather will curl, and motion will be caused, without the intervention of either attraction or repulsion, in the present sense of these terms; but this motion exhibits itself in *an alteration of shape*, which is not at all the case with the crystal. Even if the direct attraction or repulsion of the poles be rejected, we do not see how the expressed relation between the magne-crystallic axis and the direction of the magnetic resultant is possible, without including the idea of *lateral attraction* between these lines, and consequently of the mass associated with the former. In the case of flat poles, the magnetic resultant lies in a straight line from pole to pole across the magnetic field. Let us suppose, at any given moment, this line and the magne-crystallic axis of a properly suspended crystal to cross each other at an oblique angle; let the crystal be forgotten for a moment, and the attention fixed on those two lines. Let us suppose the former

line fixed, and the latter free to rotate, the point of intersection being regarded as a kind of pivot round which it can turn. On the evolution of the magnetic force, the magne-crystallic axis *will* turn and set itself alongside the magnetic resultant. The matter may be rendered very clear by taking a pair of scissors, partly open, in the hand, holding one side fast, and then closing them. The two lines close in a manner exactly similar; and all that is required to make the illustration perfect, is to suppose this power of closing suddenly developed *in the scissors themselves*. How should we name a power resident in the scissors and capable of thus drawing the blades together? It may be called a 'tendency,' or an 'endeavour,' but the word *attraction* seems to be as suitable as either.

The symmetry of crystalline arrangement is annihilated by reducing the mass to powder. 'That force among the particles which makes them cohere in regular order' is here ineffective. The magne-crystallic force, in short, is reduced to nothing, but we have the same results. If, then, the principle of elective polarity, the mere modification of magnetism or diamagnetism by mechanical arrangement, be sufficient to explain the entire series of crystalline phenomena in the magnetic field, why assume the existence of this new force, the very conception of which is attended with so many difficulties?¹

¹ 'Perhaps,' says Mr. Faraday, in a short note referring to 'the strange and striking character' of these forces, 'these points may find their explication hereafter in the action of contiguous particles.'

APPLICATION OF THE PRINCIPLE OF ELECTIVE POLARITY TO CRYSTALS.

We shall now endeavour to apply the general principle of elective polarity to the case of crystals. This principle may be briefly enunciated as follows :—

If the arrangement of the component molecules of any crystal be such as to present different degrees of proximity in different directions, then the line of closest proximity, other circumstances being equal, will be that chosen by the respective forces for the exhibition of their greatest energy. If the mass be magnetic, this line will set axial; if diamagnetic, equatorial.

From this point of view, the deportment of the two classes of crystals, represented by Iceland spar and carbonate of iron, presents no difficulty. This crystalline form is the same; and as to the arrangement of the molecules, what is true of one will be true of the other. Supposing, then, the line of closest proximity to coincide with the optic axis; this line, according to the principle expressed, will stand axial or equatorial, according as the mass is magnetic or diamagnetic, which is precisely what the experiments with these crystals exhibit.

Analogy, as we have seen, justifies the assumption here made. It will, however, be of interest to inquire, whether any discoverable circumstance connected with crystalline structure exists, upon which the difference of proximity depends; and, knowing which, we can pronounce with tolerable certainty, as to the position which the crystal will take up in the magnetic field.

The following experiments will perhaps suggest a reply.

If a prism of sulphate of magnesia be suspended between the poles with its axis horizontal, on exciting the magnet the axis will take up the equatorial position. This is not entirely due to the form of the crystal; for even when its

axial dimension is shortest, the axis will assert the equatorial position ; thus behaving like a magnetic body, setting its longest dimension from pole to pole.

Suspended from its end with its axis vertical, the prism will take up a determinate oblique position. When the crystal has come to rest, let that line through the mass which stands exactly equatorial be carefully marked. Lay a knife-edge along this line, and press it in the direction of the axis. The crystal will split before the pressure, disclosing shining surfaces of cleavage. This is the only cleavage the crystal possesses, and it stands equatorial.

Sulphate of zinc is of the same form as sulphate of magnesia, and its cleavage is discoverable by a process exactly similar to that just described. Both crystals set their planes of cleavage equatorial. Both are diamagnetic.

Let us now examine a magnetic crystal of similar form. Sulphate of nickel is, perhaps, as good an example as we can choose. Suspended in the magnetic field with its axis horizontal, on exciting the magnet the axis will set itself from pole to pole ; and this position will be persisted in, even when the axial dimension is shortest. Suspended from its end, the crystalline prism will take up an oblique position with considerable energy. When the crystal thus suspended has come to rest, mark the line along its end which stands *axial*. Let a knife-edge be laid on this line, and pressed in a direction parallel to the axis of the prism. The crystal will yield before the edge, and discover a perfectly clean plane of cleavage.

These facts are suggestive. The crystals here experimented with are of the same outward form ; each has but one cleavage : and the position of this cleavage, with regard to the form of the crystal, is the same in all. The magnetic force, however, at once discovers a difference of action. *The cleavages of the diamagnetic specimens stand equatorial ; of the magnetic, axial.*

A cube cut from a prism of scapolite, the axis of the prism being perpendicular to two of the parallel faces of the cube, suspended in the magnetic field, sets itself with the axis of the prism from pole to pole.

A cube of beryl, of the same dimensions, with the axis of the prism from which it was taken also perpendicular to two of the faces, suspended as in the former case, sets itself with the axis equatorial. Both these crystals are magnetic.

The former experiments showed a dissimilarity of action between magnetic and diamagnetic crystals. In the present instances both are magnetic, but still there is a difference; the axis of the one prism stands axial, the axis of the other equatorial. With regard to the explanation of this, the following fact is significant. Scapolite cleaves *parallel* to its axis, while beryl cleaves *perpendicular* to its axis; the cleavages in both cases, therefore, stand axial, thus agreeing with sulphate of nickel. The cleavages hence appear to take up a determinate position, regardless of outward form, and they seem to exercise a ruling power over the deportment of the crystal.

A cube of saltpetre, suspended with the crystallographic axis horizontal, sets itself between the poles with this axis equatorial.

A cube of topaz, suspended with the crystallographic axis horizontal, sets itself with this axis from pole to pole.

We have here a kind of complementary case to the former. Both these crystals are diamagnetic. Saltpetre cleaves parallel to its axis; topaz perpendicular to its axis. The planes of cleavage, therefore, stand in both cases equatorial, thus agreeing with sulphate of zinc and sulphate of magnesia.¹

¹ Topaz possesses other cleavages, but for the sake of simplicity we have not introduced them; more especially as they do not appear to vitiate the action of the one introduced, which is by far the most complete.

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maline, on the contrary, retain their directive power, for in their case the cleavages are unaffected. The deportment of rock crystal, whose weakness of action appears to have taken both Faraday and Plücker by surprise —as here the optic axis force, without assigning any reason, has thought proper to absent itself almost totally —follows at once from the homogeneous nature of its mass; it is almost like glass, which possesses no directive power; its cleavages are merely traces of cleavage. If, instead of possessing planes of cleavage, a crystal be composed of a bundle of fibres, the forces may be expected to act with greater energy along the fibre than across it. Anything, in short, that affects the mechanical arrangement of the particles will affect, in a corresponding degree, the line of elective polarity. There are crystals which are both fibrous and have planes of cleavage, the latter often perpendicular to the fibre; in this case two opposing arrangements are present, and it is difficult to pronounce beforehand which would predominate.¹

The same difficulty extends to crystals possessing several planes of cleavage, oblique to each other, and having no common direction. In many cases, however, the principle may be successfully applied. We shall content ourselves in making use of it to explain the deportment of that class of crystals, of which, as to form, Iceland spar is the type.

For the sake of simplicity, we will commence our demonstration with an exceedingly thin rhombus cloven from this crystal. Looking down upon the flat surface of such a rhombus, what have we before us? It is cleavable parallel to the four sides. Hence our answer must be, ‘an indefinite number of smaller rhombuses held symmetrically together by the force of cohesion.’ Let us confine

¹ It is probable that the primitive plates themselves have different arrangements of the molecules *along* and *across* them.

our attention, for a moment, to two rows of these rhombuses; the one ranged along the greater diagonal, the other along the less. A moment's consideration will suffice to show, that whatever be the number of small rhombuses supposed to stand upon the long diagonal, precisely the same number must fit along the short one; but in the latter case *they are closer together*. The matter may be rendered very plain by drawing a lozenge on paper, with opposite acute angles of 77° , being those of Iceland spar. Draw two lines, a little apart, parallel to opposite sides of the lozenge, and nearly through its centre; and two others, the same distance apart, parallel to the other two sides of the figure. The original rhombus is thus divided into four smaller ones; two of which stand upon the long diagonal, and two upon the short one, each of the four being separated from its neighbour by an interval which may be considered to represent the interval of cleavage in the crystal. The two which stand upon the long diagonal, L , have their acute angles opposite; the two which stand upon the short diagonal, s , have their obtuse angles opposite. The distance between the two former, across the interval of cleavage, is to the distance between the two latter, as L is to s , or as the cosine of $38^\circ 30'$ to its sine, or as $4 : 3$. We may conceive the size of these rhombuses to decrease till they become molecular; the above ratio will then appear in the form of a differential quotient, but its value will be unaltered. Here, then, we have along the greater diagonal a row of magnetic or diamagnetic molecules, the distance between every two being represented by the number 4; and along the short diagonal a row of molecules, the distance between every two being represented by the number 3. In the magnetic field, therefore, the short diagonal will be the line of elective polarity; and in magnetic crystals will stand axial, in diamagnetic equatorial, which is precisely the

case exhibited by experiment. Thus the apparent anomaly of carbonate of lime setting its long diagonal axial, and carbonate of iron its short diagonal axial, seems to be fully explained; the position of the former line being due, not to any endeavour on its part to stand parallel with the magnetic resultant, but being the simple consequence of the repulsion of the short diagonal.

There is no difficulty in extending the reasoning used above to the case of full crystals. If this be done, it will be seen that the line of closest proximity coincides with the optic axis, which axis, in the magnetic field, will signalise itself accordingly. A remarkable coincidence exists between this view and that expressed by Mitscherlich in his beautiful investigation on the expansion of crystals by heat.¹ ‘If,’ says this gifted philosopher, ‘we imagine the repulsive force of the particles increased by the accession of heat, then we must conclude that the line of greatest expansion will be that in which the atoms lie most closely together.’ This line of greatest expansion Mitscherlich found, in the case of Iceland spar, to coincide with the optic axis. The same conclusion has thus been arrived at by two modes of reasoning, as different as can well be conceived.

If, then, speculation and experiment concur in pronouncing the line of closest proximity among the particles to be that in which the magnetic and diamagnetic forces will exhibit themselves with peculiar energy, thus determining the position of the crystalline mass between the poles, we are furnished with a valuable means of ascertaining the relative values of this proximity in different directions through the mass. An *order of contact* might, perhaps, by this means be established, of great interest in a mineralogical point of view. In the case of a right rhombic prism, for example, the long diagonal of the

¹ Poggendorff's *Annalen*, vol. x. p. 138.

base may denote an order of contact very different from that denoted by the short one; and the line at right angles to the diagonals, that is, the axis of the prism, a contact very different from both. We can compare these lines two at a time. By hanging the short diagonal vertical in the magnetic field, its rotatory power is annulled, and we can compare the long diagonal and the axis. By hanging the long diagonal vertical, we can compare the short diagonal and the axis. By hanging the axis vertical, we can compare the two diagonals. From this point of view the deportment of heavy spar and cœlestine, so utterly irreconcilable with the assumption of an optic axis force, presents no difficulty. If we suppose the proximity along the axis of the prism to be *intermediate* between the proximities along the two diagonals, the action of both crystals follows as a necessary consequence. Suspended from one angle, the axis must stand from pole to pole; from the other angle, it must stand equatorial.

A ball of dough, made from bismuth powder, was placed between two bits of glass and pressed to the thickness of a quarter of an inch. It was then set edgewise between the plates and pressed again, but not so strongly as in the former case. A model of heavy spar was cut from the mass, so that the shorter diagonal of its rhombic base coincided with the line of greatest compression, the axis of the model with the direction of less compression, and the longer diagonal of the base with that direction in which no pressure had been exerted. *When this model was dried and suspended in the magnetic field, there was no recognisable difference between its deportment and that of heavy spar.*

When a crystal cleaves symmetrically in several planes, all parallel to the same straight line, and, at the same time, in a direction perpendicular to this line, then the

latter cleavage, if it be more eminent than the former, may be expected to predominate ; but when the cleavages are oblique to each other, the united action of several minor cleavages may be such as to overcome the principal one, or so to modify it that its action is not at all the same as that of a cleavage of the same value unintersected by others. A complex action among the particles of the crystal itself may contribute to this result, and possibly in some cases modify even the influence of proximity. If we hang a magnetic body between the poles, it always shows a preference for edges and corners, and will spring to a *point* much more readily than to a *surface*. Diamagnetic bodies, on the contrary, will recede from edges and corners. *A similar action among the crystalline particles may possibly bring about the modification we have hinted at.*

During this investigation a great number of crystals have passed through our hands, but it is useless to cumber the reader with a recital of them. The number of natural crystals have amounted to nearly one hundred ; while through the accustomed kindness of Professor Bunsen, the entire collection of artificial crystals, which his laboratory contains, has been placed at our disposal.¹

We now pass over to a brief examination of the basis on which the second law rests—the affirmation, namely, that ‘the magnetic attraction decreases in a quicker ratio than the repulsion of the optic axis.’ The ingenuity of this hypothesis, and its apparent sufficiency to account for the phenomena observed by Plücker, are evident. It will be seen, however, that this repulsion arises from quite another cause—a source of error which has run undetected through the entire series of this philosopher’s inquiries.

¹ We gladly make use of this opportunity to express our obligation to Dr. Debus, the able assistant in the chemical laboratory.

The following experiment is a type of those which led Plücker to the above conclusion. A tourmaline crystal 36 millimeters long and 4 millimeters wide was suspended between a pair of pointed movable poles, so that it could barely swing between them. It set its length *axial*. On removing the poles to a distance and again exciting the magnet the crystal set *equatorial*. The same occurred, if the poles were allowed to remain as in the former case, when the crystal was raised above them or sunk beneath them. *Thus, as the crystal was withdrawn from the immediate neighbourhood of the poles it turned gradually round and finally set itself equatorial.*¹

A similar action was observed with staurolite, beryl, idocrase, smaragd, and other crystals.

We have repeated these experiments in the manner described, and obtained the same results. A prism of tourmaline three-quarters of an inch long and a quarter of an inch across was hung between a pair of poles with conical points, an inch apart. On exciting the magnet the crystal set axial. When the poles were withdrawn to a distance, on the evolution of the force the crystal set equatorial. An exceedingly weak current was here used; a single Bunsen's cell being found more than sufficient to produce the result.

According to the theory under consideration, the tourmaline, in the first instance, stood from pole to pole because the magnetism was strong enough to overcome the repulsion of the optic axis. This repulsion, decreasing more slowly than the magnetic attraction, necessarily triumphed when the poles were removed to a sufficient distance. Between a pair of flat poles, however, this same crystal could *never* take up the axial position. On bring-

¹ Poggendorff's *Annalen*, vol. lxxii. p. 31.

ing the faces within half an inch of each other, and exciting the magnet by a battery of thirty-two cells, the crystal vibrated between the faces without touching either. The same occurred when one cell, six cells, twelve cells, and twenty cells, respectively, were employed.

If the attraction increases, as stated, more quickly than the hypothetic repulsion, how can the impotence of attraction in the case before us be accounted for? We have here a powerful current, and poles only half an inch apart; power and proximity work together, but their united influence is insufficient to pull the crystal into the axial line. The cause of the phenomenon must it seems be sought, not in optic repulsion, but in the manner in which the magnetic force is applied. The crystal is strongly magnetic, and the pointed poles exercise a concentrated *local* action. The *mass* at both ends of the crystal, when in the neighbourhood of the points, is powerfully attracted, while the action on the central parts, on account of their greater distance, is comparatively weak. Between the flat poles, on the contrary, the crystal finds itself, as it were, totally immersed in the magnetic influence; its entire mass is equally affected, and the whole of its directive power developed. The similarity of action between the flat poles and the points, *withdrawn to a distance*, is evident. In the latter case, the force, radiating from the points, has time to diffuse itself, and fastens almost uniformly upon the entire mass of the crystal, thus calling forth, as in the former case, its directive energy; and the equatorial position is the consequence. The disposition of the lines of force, in the case of points, is readily observed by means of iron filings, strewn on paper and brought over the poles. When the latter are near each other, on exciting the magnet, the filings are gathered in and stretch in a rigid line from point to point; according as the poles are withdrawn, the magnetic curves take

a wider range, and at length attain a breadth sufficient to encompass the entire mass of the crystal.¹

As the *local attraction* of the mass in the case of magnetic crystals deranges the directive power and overcomes it, so will the *local repulsion* of the mass in diamagnetic crystals. A prism of heavy spar, whose length was twice its breadth, hung from its acute angle, stood between the flat poles axial, between the points equatorial. On making its length and breadth alike, the axis of the prism stood from pole to pole, whether the conical points or flat faces were used. Shortening the axial direction a little more, and suspending the crystal from its obtuse angle, the axis between the flat poles stood equatorial, and, consequently, the longest dimension of the crystal, axial; between the points, owing to the repulsion of the extreme ends, the length stood equatorial. Similar experiments were made with celestine and topaz; but all with the same general result.

'I had the advantage,' says Faraday, 'of verifying Plücker's results under his own personal tuition, in respect of tourmaline, staurolite, red ferrocyanide of potassium, and Iceland spar. Since then, and in reference to the present inquiry, I have carefully examined calcareous spar, as being that one of the bodies which was at the same time free from magnetic action, and so simple in its crystalline relations as to possess but one optic axis.

'When a small rhomboid about 0·3 of an inch in its greatest dimension was suspended with its optic axis horizontal between the pointed poles of the electro-magnet, approximated as closely as they can be to allow free motion, the rhomboid set in the equatorial direction, and the optic axis coincided with the magnetic axis; but if the poles be separated to the distance of a half or three-quarters of an

¹ Faraday has already pointed out 'the great value of a magnetic field of uniform force.'—Phil. Trans., 1849, p. 4.

inch, the rhomboid turned through 90° and set with the optic axis in the equatorial direction, and the greatest length axial. In the first instance the diamagnetic force overcame the optic axis force ; in the second the optic axis force was the stronger of the two.'

The foregoing considerations will, we believe, render it very clear that the introduction of this optic axis force is altogether unnecessary ; the case being simply one of local repulsion. Faraday himself found that the crystal between the flat poles could *never* set its optic axis from pole to pole ; between the points alone was the turning round of the crystal possible. We have made the experiment. A fine large crystal of Iceland spar, suspended between the near points, set its optic axis from point to point ; between the distant points the axis stood equatorial. The crystal was then removed from the magnetic field, placed in an agate mortar and pounded to powder. The powder was dissolved in muriatic acid. From the solution it was precipitated by carbonate of ammonia. The precipitate thus obtained, as is well known, is exactly of the same chemical constitution as the crystal. This precipitate was mixed with gum water and squeezed in one direction. From the mass thus squeezed a model of Iceland spar was made, the line of greatest compression through the model coinciding with that which represented the optic axis. *This model imitated, in every respect, the deportment observed by Faraday.* Between the near points the optic axis stood from point to point, between the distant points equatorial. It cannot, however, be imagined that the optic axis force survived the pounding, dissolving, and precipitating. Further, this optic axis force is a sword which cuts two ways ; if it be assumed repulsive, then the deportment of the compound carbonate of lime and iron is unexplainable ; if attractive, it fails in the case of Iceland spar.

It is a remarkable fact, that all those crystals which exhibit this phenomenon of turning round, cleave either perpendicular to their axes or oblique to them, furnishing a resultant which acts in the direction of the perpendicular. Beryl is an example of the former ; the crystal just examined, Iceland spar, is an example of the latter. This is exactly what must have been expected. In the case of a magnetic crystal, cleavable parallel to its length alone, there is no reason present why the axial line should ever be forsaken. But if the cleavages be transverse, or oblique, so as to furnish a line of elective polarity in the transverse direction, two diverse causes come into operation. By virtue of its magnetism, the crystal seeks to set its length axial, as a bit of iron or nickel would do ; but in virtue of its *molecular structure*, it seeks to place a line at right angles to its length axial. For the reasons before adduced, if the *near* points be used, the former is triumphant ; if the points be distant, the latter predominates.

We noticed in a former paper a description of gutta-percha of a fibrous texture, which, on being suspended between the poles, was found to accept magnetic induction with peculiar facility along the fibre. A piece was cut from this substance, of exactly the same size as the tourmaline crystal, described at the commencement of this section. The fibre was transverse to the length of the piece. Suspended in the magnetic field, the gutta-percha exhibited all the phenomena of the crystal.

One of the sand-paper models before described is still more characteristic as regards this turning round on the removal of the poles to a distance. We allude to that whose magnetic layers of emery are perpendicular to its length. The deportment of this model, if we except its greater energy, is not to be distinguished from that of a prism of beryl. Between the near points both model and crystal set axial, between the distant points equatorial,

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while between the flat poles the deportment, as before described, is exactly the same. The magnetic laminæ of beryl occupy the same position, with regard to its axis, as the magnetic laminæ of the model, with regard to *its* axis. There is no difference in construction, save in the superior workmanship of nature, and there is no difference at all as regards deportment. Surely these considerations suggest a common origin for the phenomena exhibited by both.

We have the same action in the case of the compressed dough, formed respectively from the powdered carbonate of iron and powdered bismuth. A plate of the former, three-quarters of an inch square and one-tenth of an inch in thickness, stands between the conical poles, brought within an inch of each other, exactly axial; between the same poles, two inches apart, it stands equatorial. A plate of compressed bismuth dough stands, between the near points, equatorial, between the distant points, axial.

Any hypothesis which solves these experiments must embrace crystalline action also; for the results are not to be distinguished from each other. But in the above cases an optic action is out of the question. With the similarity of structure between beryl and the sand-paper model, above described—with the complete identity of action which they exhibit, before us, is it necessary, in explanation of that action, to assume the existence of a force which, in the case of the crystal, is all but inconceivable, and in the case of the model is not to be thought of? In his able strictures on the theory of M. Becquerel,¹ Plücker himself affirms, that we have no example of a force which is not associated with ponderable matter. If this be the case as regards the optic axis force, if the attraction and repulsion attributed to it be actually exerted on the mass of the crystal, *how is it to be distinguished from magnetism or diamagnetism?* The assumption of

¹ Poggendorff's *Annalen*, vol. lxxvii. p. 578.

Faraday appears to be the only refuge here: the denial of attraction and repulsion altogether.

In the first section of this memoir it has been proved, by the production of numerous exceptions, that the law of Plücker, as newly revised, is untenable. It has also there been shown, that the experiments upon which Faraday grounds his hypothesis of a purely directive force, are referable to quite another cause. In the second section an attempt has been made to connect this cause with crystalline structure, and to prove its sufficiency to produce the particular phenomena exhibited by crystals. In the third section we find the principle entering into the most complicated instances of these phenomena, and reducing them to cases of extreme simplicity. The choice, therefore, rests between the assumption of *three new forces* which seem but lamely to execute their mission, and that simple modification of existing forces, to which we have given the name elective polarity, and which seems sufficiently embracing to account for all.

It appears then to be sufficiently established, that from the deportment of crystalline bodies in the magnetic field, no direct connection between light and magnetism can be inferred. A rich possession, as regards physical discovery, seems to be thus snatched away from us; but the result will be compensatory. That a certain relation exists, with respect to the path chosen by both forces through transparent bodies, must be evident to any one who carefully considers the experiments described in this memoir. The further examination of this deeply interesting subject we defer to another occasion.

Nature acts by general laws, to which the terms great and small are unknown; and it cannot be doubted that the modifications of magnetic force, exhibited by bits of copperas and sugar in the magnetic field, display them-

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selves on a large scale in the crust of the earth itself. A lump of stratified grit exhibits elective polarity. It is magnetic, but will set its planes of stratification from pole to pole, though it should be twice as long in the direction at right angles to these planes. A new factor appears thus to enter our speculations as to the position of the magnetic poles of our planet—the influence of stratification and plutonic disturbance upon the magnetic and electric forces.

MARBURG: May, 1850.

Note, 1870.—I wish to direct attention here to a paper written by Plücker, and translated by myself, for the new series of ‘Scientific Memoirs,’ published by Taylor and Francis (1853). In this paper Plücker approached much more closely than he had previously done to the views expressed in the foregoing memoir. But his paper, which had been written in December, 1849, remained unprinted till 1852.—J. T.

SECOND MEMOIR.

ON DIAMAGNETISM AND MAGNE-CRYSTALLIC ACTION.

[This investigation was conducted by me in the laboratory of Professor Magnus, of Berlin, during the spring of 1851, and it was communicated to the British Association at its meeting at Ipswich the same year. It was also published in the 'Philosophical Magazine' for September, 1851.—J. T. 1870.]

§ 1. *On Diamagnetism.*

FIVE years ago Faraday established the existence of the force called diamagnetism, and from that time to the present some of the first minds in Germany, France, and England have been devoted to the investigation of this subject. One of the most important aspects of the inquiry is the relation which subsists between magnetism and diamagnetism. Are the laws which govern both forces identical? Will the mathematical expression of the attraction in the one case be converted into the expression of the repulsion in the other by a change of sign from positive to negative?

The conclusions arrived at by Plücker in this field of inquiry are exceedingly remarkable and deserving of attention. His first paper, 'On the relation of Magnetism and Diamagnetism,' is dated from Bonn, September 8, 1847, and will be found in Poggendorff's *Annalen* and in Taylor's 'Scientific Memoirs.' He sets out with the question, 'Is it possible, by mixing a magnetic substance with

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a diamagnetic, so to balance the opposing forces that an indifferent body will be the result?' This question he answers in the negative. 'The experiments,' he writes, 'which I am about to describe, render it necessary that every thought of the kind should be abandoned.'

One of these experiments will serve as a type of the whole, and will show the foundation on which the negative reply rests. A piece of cherry-tree bark, 15 millims. long and 7 millims. wide, was suspended freely between the two movable poles of an electro-magnet; on bringing the points of the poles so near each other that the bark had barely room to swing between them, it set itself, like a diamagnetic substance, with its length *perpendicular* to the line which united the two poles. On removing the poles to a distance, or on raising the bark to a certain height above them, it turned round and set its length *parallel* to the line joining the poles. As usual, I shall call the former position the *equatorial*, and the latter position the *axial*. Thus when the poles were near, diamagnetism was predominant, and caused the mass to set equatorial; when the poles were distant, magnetism, according to the notion of Plücker, was predominant, and caused the mass to set axial. From this he concludes, '*That in the cherry-tree bark two distinct forces are perpetually active; and that one of them, the magnetic, decreases more slowly with the distance than the other, the diamagnetic.*'

In a later memoir¹ this predominance of the diamagnetic force at a short distance is affirmed to be due to the more general law, that when a magnet operates upon a substance made up of magnetic and diamagnetic constituents, if the power of the magnet be increased, the diamagnetism of the substance increases in a much quicker ratio than the magnetism; so that,

¹ Poggendorff's *Annalen*, vol. lxxv. p. 413.

without altering the distance between it and the magnet, the same substance might at one time be attracted, and at another time repelled, by merely varying the strength of the exciting current.

This assertion is supported by a number of experiments, in which a watch-glass containing mercury was suspended from one end of a balance. The watch-glass was magnetic, the mercury was diamagnetic. When the glass was suspended at a height of 3·5 millims. above the pole of the magnet, and the latter was excited by a battery of four cells, an attraction of one milligramme was observed; when the magnet was excited by eight cells, the attraction passed over into a repulsion of the same amount.

It is to be regretted that Plücker, instead of giving us the actual strength of the exciting current, has mentioned merely the number of cells employed. From this we can get no definite notion as to the amount of magnetic force evolved in the respective cases. It depends of course upon the nature of the circuit whether the current increases with the number of cells or not. If the exterior resistance be small, an advance from four to eight cells will make very little difference; if the outer resistance be a vanishing quantity, one cell is as good as a million.¹

During an investigation on the magneto-optic properties of crystals,² which I had the pleasure of conducting in connection with my friend Professor Knoblauch, I had repeated opportunities of observing phenomena exactly similar to those observed with the cherry-tree bark; but a close study of the subject convinced me that the explanation of these phenomena by no means necessitated the hypothesis of two forces acting in the manner

¹ The usual arrangement of the cells is here assumed; that is, where the negative component of one cell is connected with the positive component of the next.

² Phil. Mag., July 1850.

described. Experiment further convinced me, that a more delicate apparatus than the balance used by Plücker would be better suited to the measurement of such feeble manifestations of force.

An exact acquaintance with electro-magnetic attractions appeared to be a necessary discipline for the successful investigation of diamagnetic phenomena; and pursuing this idea, an inquiry was commenced last November into the action of an electro-magnet upon masses of soft iron. I was finally led to devote my entire attention to the attraction of soft iron spheres, and the results obtained were so remarkable as to induce me to devote a special memoir to them alone.¹

In this investigation it was proved, that a ball of soft iron, separated by a small fixed distance from the pole of an electro-magnet, was attracted with a force exactly proportional to the square of the exciting current.² Now this attraction is in each case the produce of two factors, one of which represents the magnetism of the magnet, and the other the magnetism of the ball. For example, if the magnetism of the magnet at any given moment be represented by the number 4, and that of the ball by 3, the attraction, which is a consequence of their reciprocal action, is represented by the product 12. If we now suppose the magnetism of the magnet to be doubled by a current of double strength, the ball will have its magnetism also doubled, and the attraction resulting will be expressed by 8×6 , or 48. Thus we see that the doubling of the power of the magnet causes four times the attraction; and that while the attraction increases as the square of the current, the magnetism of the ball increases in the simple ratio of the current itself.

¹ Phil. Mag., April 1851. Poggendorff's *Annalen*, May 1851.

² This had been already proved by Lenz and Jacobi, but the employment of the iron spheres renders the result particularly sharp and exact.

The way to a comparison of magnetism and diamagnetism is thus cleared. We know the law according to which the magnetism of an iron ball increases, and we have simply to ascertain whether the diamagnetism of a bismuth ball follows the same law. For the investigation of this question I constructed the following apparatus.

In two opposite sides of a square wooden box were sawn two circular holes about four inches in diameter. The holes were diagonally opposite to each other, and through each a helix of copper wire was introduced and wedged fast. Each helix contained a core of soft iron, which was pushed so far forward that a line parallel to the sides of the box through which the helices entered, and bisecting the other two sides, was a quarter of an inch distant from the interior end of each core. The distance between the two interior ends was six inches, and in this space a little beam of light wood was suspended. At the ends of the beam two spoon-shaped hollows were worked out, in which a pair of small balls could be conveniently laid. The beam rested in a paper loop, which was attached to one end of a fine silver wire. The wire passed upward through a glass tube nearly three feet in length, and was connected at the top with a torsion head. The tube was made fast in a stout plate of glass, which was laid upon the box like a lid, thus protecting the beam from currents of air. A floor of Bristol board was fixed a little below the level of the axes of the cores, the 'board' being so cut as to fit close to the helices: the two corners of the floor adjacent to the respective cores and diagonally opposite to each other, bore each a graduated quadrant. When the instrument was to be used, two balls of the substance to be experimented with were placed upon the spoon-shaped hollows of the beam and exactly balanced. The balance was established by pushing the beam a little in the required direction through the paper loop in which

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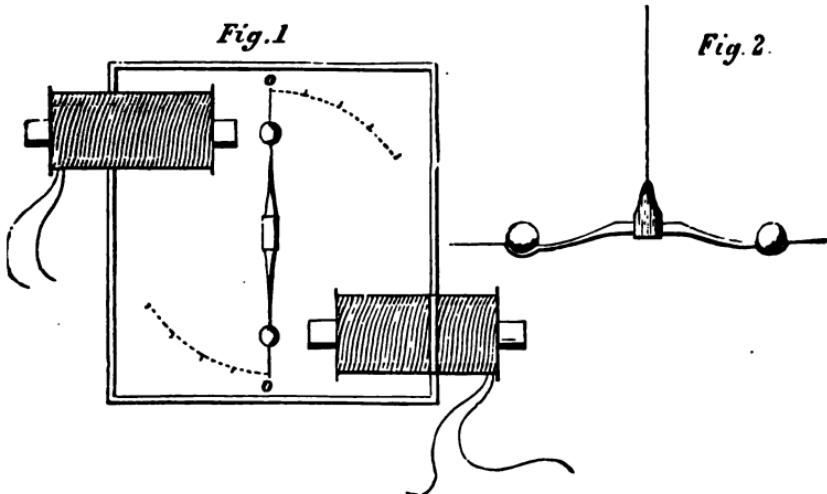
it loosely rested ; and to accomplish this with greater ease, two square pieces were sawn out of the sides of the box, and two others were exactly fitted into the spaces thus opened ; these pieces could be taken out at pleasure, and the hand introduced without raising the lid. The torsion-head was arranged so that when the beam bearing the balls came to rest, a thin glass fibre attached to the beam pointed to zero on the graduated quadrant underneath, while the index of the head pointed also to the zero of the graduated circle above. A current was sent through the helices so as to cause the two magnetic poles which operated on the diamagnetic balls to be of opposite polarities. The balls were repelled when the current flowed. Preserving the current constant, the index above was turned in a direction opposed to the repulsion until the beam stood again at zero. The torsion necessary to effect this is evidently the expression of the repulsive force exerted at this particular distance.

Fig. 1 represents the appearance of the beam and helices when looked down upon through the glass lid. Fig. 2 represents the beam and balls attached to the suspending wire.

When the glass index pointed to zero, an interval of about $\frac{1}{12}$ th of an inch usually separated the nearest surfaces of the diamagnetic balls from the core ends. The intensity of the current was measured by a tangent galvanometer, and it was varied by means of a rheostat. Always before commencing a series of experiments, the little beam was tested. With very strong currents it was found to be slightly diamagnetic ; but so feeble, that its action, even supposing it not to follow the same law of increase as the ball (which, however, it certainly does), could cause no measurable disturbance.

I neglected no precaution to secure the perfect purity of the substances examined. The entire investigation was

conducted in the private cabinet of Professor Magnus in Berlin; and at the same time Dr. Schneider happened to be engaged in the professor's laboratory in determining



the atomic weight of bismuth. He was kind enough to give me a portion of this substance, prepared in the following way:—The metal of commerce was dissolved in nitric acid and precipitated with distilled water; whatever iron was present remained in the solution. The precipitate was filtered, washed for six days successively, and afterwards reduced by means of black flux. The metal thus obtained was again melted in a Hessian crucible, and saltpetre was gradually added, the mass at the same time being briskly stirred. Every remaining trace of foreign ingredient was thus oxidised and rose to the surface, from which it was carefully skimmed. The metal thus purified was cast into a bullet-mould, the interior surface of which was coated by a thin layer of oil; the outer surface of each bullet was carefully scraped away with glass, the ball was then scoured with sea-sand, and finally boiled in hydrochloric acid. The bismuth balls thus purified were

placed upon the hollows of the beam, Fig. 2, and their repulsions by currents of various strengths determined in the manner indicated. The series of repulsions thus obtained are exactly analogous to the series of attractions in the experiments with the balls of iron. Now the square roots of the *attractions* give a series of numbers exactly proportional to the currents employed; and the question to be decided is,—‘Will the square roots of the *repulsions* give a similar series, or will they not?’

Calling the angle which the needle of the tangent compass, under the influence of the current, makes with the magnetic meridian α , then if the repulsion of the bismuth ball follow the same law as the attraction of the iron one, we shall have the equation

$$\sqrt{T} = n \tan \alpha,$$

where T represents the torsion necessary to bring the beam back to zero, and n is a constant depending on the nature of the experiment. The following tables will show the fulfilment or non-fulfilment of this equation:—

Table I.—Bismuth spheres, 8 millims. diameter.

$$n=11.7.$$

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
10°	0.176	5	2.23	2.06
20	0.364	16.3	4.04	4.25
30	0.577	42.3	6.50	6.74
35	0.700	64	8	8.19
40	0.839	100	10	9.81
45	1.000	136	11.66	11.7
50	1.192	195	13.96	13.95

A second series was made with a pair of spheres of the bismuth of commerce with the same result.

Sulphur is also a diamagnetic substance, but a much

weaker one than bismuth. The next series of experiments were made with two balls of this substance.

*Table II.—Sulphur spheres, 8 millims. diameter.
n=3·3.*

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
20° 0	0·364	1·2	1·10	1·20
30 45	0·595	3·0	1·73	1·96
41 20	0·880	8·0	2·83	2·90
54 0	1·376	21·0	4·58	4·54

A pair of sulphur balls were next taken of nearly twice the diameter of the preceding.

*Table III.—Sulphur spheres, 13·4 millims. diameter.
n=6·7.*

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
20° 0	0·364	6·2	2·45	2·44
30 45	0·595	15·0	3·87	3·98
41 20	0·880	34·5	5·90	5·89
54 0	1·376	89·0	9·43	9·22

The sulphur from which these balls were made was the material of commerce. After the experiments one of the balls was placed in a clean porcelain crucible and brought over the flame of a spirit-lamp; the sulphur melted, ignited, and disappeared in sulphurous acid vapour. A portion of solid substance remained in the crucible unvolatilised. This was dissolved in hydrochloric acid, and ferrocyanide of potassium was added; the solution turned immediately blue; iron was present. The other ball was submitted to a similar examination, and with the same result; both balls contained a slight admixture of iron.

In this case, therefore, the two opposing forces, magnet-

ism and diamagnetism, were actually present, but we find the equation $\sqrt{T} = n \tan \alpha$ fulfilled notwithstanding. Did one of the forces increase with the ascending magnetic power more quickly than the other, this result would be impossible.

Flowers of sulphur were next tried, but found to contain a considerable quantity of iron. I have to thank Professor Magnus for a portion of a native crystal of the substance obtained in Sicily, which upon trial was found to be perfectly pure. From this two small pellets were formed and laid upon the torsion-balance : they gave the following results:—

Table IV.—Spheres of Native Sulphur.
 $n=2.65$.

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
20°	0.364	0.9	0.95	0.96
30	0.577	2.5	1.58	1.53
40	0.839	5.0	2.24	2.22
45	1.000	7.0	2.64	2.65
50	1.192	10.0	3.16	3.16

The next substance chosen was calcareous spar. The corners of the crystalline rhomb were first filed away, and the mass thus rendered tolerably round ; it was then placed between two pieces of soft sandstone, in each of which a hollow, like the cavity of a bullet-mould, had been worked out. By turning the stones, one right and the other left, and adding a little water, and a little patience, the crystal was at length reduced to a spherical form. The ball was then washed, and its surface carefully cleansed in dilute hydrochloric acid. The first pair of balls were from the neighbourhood of Clitheroe in Lancashire.

*Table V.—Spheres of Calcareous Spar, 9·2 millims. diameter.
n=3·7.*

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
20°	0·364	1·8	1·34	1·34
25	0·466	3·0	1·73	1·72
30	0·577	4·5	2·12	2·13
35	0·700	7·0	2·64	2·59
40	0·839	9·7	3·11	3·10
45	1·000	14·0	3·74	3·70

The spar from which these balls were taken was not quite transparent; to ascertain whether its dullness was due to the presence of iron, a crystal which weighed about 3 grammes was dissolved in hydrochloric acid; the solution was exposed in a flat basin to the air, and the iron, if present, suffered to oxidise; ferrocyanide of potassium was added, but not the slightest tinge indicative of iron was perceptible.

Experiments were next made with a pair of spheres of calcareous spar from Andreasberg in the Harz Mountains.

*Table VI.—Spheres of Calcareous Spar, 10·8 millims. diameter.
n=5.*

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
20° 0	0·364	2·8	1·68	1·82
25 0	0·466	5·0	2·21	2·33
30 0	0·577	8·0	2·83	2·83
35 0	0·700	11·2	3·35	3·50
37 30	0·767	14·5	3·81	3·83
57 0	1·540	60·0	7·75	7·70

The spar from which these balls were taken was perfectly transparent. After the experiment, they were partially dissolved in hydrochloric acid, and the solution tested as in the former case for iron. No trace of iron was present.

The conclusion to be drawn from all these experiments, and from many others which I forbear citing, is, that the law of increase for a diamagnetic body is exactly the same as for a magnetic one. I had proceeded further with this investigation than the point now attained, when I learned that a memoir on diamagnetism by M. Edmond Becquerel had appeared in the May number of the *Annales de Chimie et de Physique*.¹ In this memoir the views of the Bonn philosopher are also controverted, and a number of experiments are adduced to prove the identity of the laws which regulate magnetic attraction and diamagnetic repulsion. The argument employed by M. Becquerel is the same in principle as that furnished by the foregoing experiments. He proves that the repulsion of bars of bismuth, sulphur and wax, increases as the square of the exciting current, and that the attraction of a little bar of iron follows the same law. We have both been guided in our inquiries by the same fundamental thought, though our modes of carrying out the thought are different.

¹ In fact M. Edmond Becquerel had proved, in the year 1850, that diamagnetic repulsion followed the law of squares. My experiments on this subject, though different in form, are to be regarded as mere verifications of his. See *Annales de Chimie et de Physique*, vol. xxviii. p. 301. In the very able memoir referred to in the text, he amply illustrates the law of attraction and repulsion; and there also he repeats the theoretic conclusion already adverted to, which in his own words is this:—

‘Cette hypothèse consiste à supposer qu'il n'y a pas deux genres d'actions différentes produites sur les corps par les aimants, actions magnétiques et actions diamagnétiques, mais bien un seul genre d'action, une aimantation par influence, et que la répulsion exercée sur les substances qui s'éloignent des pôles des aimants est due à ce que les corps sont entourés par un milieu plus magnétique qu'elles.’

‘Je n'ai présenté,’ he adds, ‘cette explication du diamagnétisme que pour lier entre eux, d'une manière plus simple, je crois, qu'on ne l'avait fait jusqu'ici, les effets du diamagnétisme sur les différents corps soumis à son action.’—*Annales de Chimie et de Physique*, vol. xxxii. p. 112.

I have observed many phenomena, which, without due consideration, would lead us directly to Plücker's conclusions; and a few of which may be here described. The bismuth balls were placed upon the beam, and one core was excited; on the top of the ball opposite that core, a particle of iron, not the twentieth part of a common pin-head in size, was fixed. A current of 10° circulated in the helix, and the beam came to rest at the distance of 4° from the zero of the lower graduation. The current was then permitted to increase gradually. The magnetism of the iron particle and the diamagnetism of the bismuth rose of course along with it, but the latter triumphed; the beam was repelled, and finally came to rest against a stop which was placed 9° distant.

The particle of iron was removed, and a small crystal of carbonate of iron was put in its place; a current of 15° circulated in the helix, and the beam came to rest at about 3° distant from zero. The current was raised gradually, but before it had reached 30° ,¹ diamagnetism conquered, and the beam receded to the stop as before.

Thinking that this apparent triumph of diamagnetism might be due to the fact that the crystal of carbonate of iron had become saturated with magnetism, and that it no longer followed the law of increase true for a larger piece of the substance, I tested the crystal with currents up to 49° ; the attractions were exactly proportional to the squares of the exciting currents.

Thinking also that a certain reciprocal action between the bismuth and the crystal, when both were placed together in the magnetic field, might so modify the latter as to produce the observed result, I removed the crystal, and placed a cube of the zinc of commerce upon the opposite end of the beam. The zinc was slightly mag-

¹ Currents of 10° , of 15° , of 30° , &c., signify currents which produced these respective deflections of the tangent-compass needle.

netic. Bismuth and zinc were thus separated by an interval of 6 inches ; both cores were excited by a current of 10° , and the beam, after some oscillations, came to rest at 4° distant from zero. The current was now gradually raised, but when it reached 35° of the graduated quadrant, the beam receded and was held firmly against the stop. When the circuit was broken it left the stop, and, after some oscillations, came to rest at zero.

These experiments seem fully to bear out the notion of Plücker. In each case we waited till both forces were in equilibrium ; and it might be thought that if the forces followed the same law, the beam ought not to move. Let us, however, clear the experiment of all mystery. When the beam was in equilibrium with a current of 10° , let us ask what forces were opposed to the repulsion of the bismuth ? There was, first of all, the attraction of the zinc ; but besides this, there was a torsion of 4° ; for the position of equilibrium for the beam with the unexcited magnet was at zero. Let us suppose the magnetism of the zinc at the distance of 4, and with the current 10° , to be equal to 8 of torsion ; this, added to the 4 already present, will give the force opposed to the bismuth ; the repulsion of the latter is therefore equal to 12. Let us now conceive the current raised from 10° to 35° , that is quadrupled.¹ Supposing the magnetism of the zinc to be increased in proportion to the strength of the current, its attraction will now be 32 ; this, added to 4 of torsion, which remains constant, makes 36, which is therefore the force exerted against the bismuth by a current of 35° under the present circumstances. But the repulsion of the bismuth being also quadrupled, it is now 48. This, opposed to a force of 36, necessarily conquers, and the beam is repelled.

We thus see that, although the magnetic force on one

¹ The tangent of 35° being four times the tangent of 10° .

side, and the diamagnetic on the other side, follow precisely the same law, the introduction of the small constant 4° entirely destroys the balance of action, so that to all appearance diamagnetism increases in a much quicker ratio than magnetism. Such a constant has probably crept into the experiments of Plücker; an inadvertency not to be wondered at, when we remember that the force was new at the time, and our knowledge of the precautions necessary for its accurate investigation very imperfect.

§ 2. On Magne-crystallic action.

Plücker has discovered that, when a crystal of pure carbonate of lime is suspended in the magnetic field with its optic axis horizontal, the said axis always sets itself equatorial. He attributed this action of the spar to a repulsion of the optic axis by the magnet, which is independent of the magnetism or diamagnetism of the mass of the crystal. It was the product of a new force, which Faraday has named 'the optic axis force.'

In the memoirs published by Knoblauch and myself, this view is controverted, and it is there proved that the action of the crystal, so far from being independent of the magnetism or diamagnetism of its mass, is totally changed by the substitution of a magnetic constituent for a diamagnetic. Our experiments led us to the conclusion, that the position of the crystal of carbonate of lime was due to the superior repulsion of the mass of the crystal in the direction of the optic axis. This view, though supported by the strongest presumptive facts, has remained up to the present time without direct proof; if, however, a difference of repulsion, such as that we have supposed, actually exists, it may be expected to manifest itself upon the torsion-balance.

But the entire repulsion of calcareous spar is so feeble, that to discover a differential action of this kind requires

great nicety of experiment. I returned to this subject three different times; twice I failed, and despaired of being able to establish a difference with the apparatus at my command. But the thought clung to me, and after an interval of some weeks, I resolved to try again.¹

The spheres of calcareous spar were placed upon the beam, and the latter was exactly balanced. The index above was so placed, that when the beam came to rest, the attached glass fibre exactly coincided with a fine black line drawn upon the Bristol board underneath. Two dots were placed upon the glass cover, about the fiftieth of an inch asunder, and the fibre was observed through the interval between them. The beam was about four inches below the cover, and parallax was thus avoided. On exciting both cores the balls receded, the index of the torsion-head was softly turned against the recession, till the fibre was brought once more into exact coincidence with the fine black line, and the torsion necessary to effect this was read off upon the graduated circle above.

The repulsion of the spheres was measured in four different directions :—

1. The optic axes were parallel to the axes of the iron cores.
2. The spheres were turned through an arc of 90° , so that the optic axes were at right angles to the cores.

¹ ‘The torsion balance was placed before a window through which the sun shone in the forenoon. In experimenting with spheres of bismuth, I was often perplexed and baffled by the contradictory results obtained at different hours of the same day. With spheres of calcareous spar, where the diamagnetic action was weaker, the discrepancies were still more striking. Once while gazing puzzled at the clear ball of spar resting on the torsion balance, my attention was drawn to the bright spot of sunlight formed by the convergence of the rays which traversed the spar, and the thought immediately occurred to me that this little “fire-place” might create currents of air strong enough to produce the observed anomalies. The shutting out of the light entirely removed the cause of the disturbance; which however was mainly due to the heating of the glass lid of the balance.’—Phil. Mag. vol. iii. p. 128.

3. The spheres were turned 90° in the same direction, so that the other ends of the axes faced the cores.

4. The spheres were turned 90° further, so that their axes were again at right angles to the cores, but with the opposite surface to that in (2) facing the latter.

The following are the respective repulsions :—

	Repulsion.
1st position	28·5
2nd position	26·5
3rd position	27·0
4th position	24·5
[Mean of repulsions along optic axis . . .	27·8
" " across " . . .	25·5
Or as 100 : 91·7]	

Each of the helices surrounding the cores was composed of two insulated wires ; the four ends of these could be so combined that the current could pass through both at the same time, as if they were a single wire, or it could be caused to traverse one wire after the other. The first arrangement was advantageous when a small exterior resistance was an object to be secured, the second when the force of the battery was such as to render exterior resistance to a certain extent a matter of indifference. In the foregoing experiments the first of these arrangements was adopted. Before commencing, I had taken fresh acid and freshly amalgamated zinc cylinders, so that the battery was in good condition. The second arrangement was then adopted, that is to say, the current was allowed to traverse one wire after the other, and the following repulsions were observed ; the numbers refer to the positions already indicated.

	Repulsion.
1st position	57
2nd position	51
3rd position	53
4th position	48
[Mean of repulsions along optic axis . . .	55
" " across " . . .	49·5
Or as 100 : 90]	

These experiments furnish the direct proof that calcareous spar is repelled most strongly in the direction of the optic axis. That Faraday has not succeeded in establishing a difference here is explained by reference to his mode of experiment. He observed the distance to which the spar was repelled, and found this the same for all positions of the crystal. The magnetic force at this distance is too weak to show a difference. In the above experiments, on the contrary, the crystal was forced back into a portion of the magnetic field where the excitement was intense, and here for the first time the difference rises to a measurable quantity.

Carbonate of iron is a crystal of the same form as calcareous spar, the iron filling up, so to speak, the exact space vacated by the calcium. This crystal is strongly magnetic; suspended in the magnetic field, that line which in calcareous spar sets equatorial, sets here axial, but with an energy far surpassing the spar; a greater differential action may therefore be anticipated.

A pair of spheres were formed from the crystal, but their attraction was so strong, that to separate them from the magnet would strain the wire beyond its limits of elasticity; one sphere only could therefore be used, the other being used as a balance-weight merely. The core opposite to the latter was removed, and the current sent round that helix only which surrounded the former. A piece of Bristol board was placed against the end of the core, and the torsion-head was so turned that when the index above pointed to zero, the little sphere was on the verge of contact. The magnet was then excited and the sphere attracted. The index was then turned in a direction opposed to the attraction until the ball gave way; the torsion necessary to effect this expresses the attraction. The crystal was first placed so that its axis was parallel to that of the magnet, and afterwards so that it was perpen-

dicular to the same. The following tables exhibit the results in both cases respectively :—

Table VII.—Carbonate of Iron. Axis of Crystal parallel to axis of Magnet. n=25·5.

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
15	0·268	43	6·56	6·57
20	0·364	80	8·94	8·91
25	0·466	129	11·36	11·42
30	0·577	200	14·14	14·14

Table VIII.—Carbonate of Iron. Axis of Crystal perpendicular to axis of Magnet. n=20·7.

α	$\tan \alpha$	T	\sqrt{T}	$n \tan \alpha$
15	0·268	30·5	5·52	5·55
20	0·364	56·0	7·48	7·53
25	0·466	92·5	9·62	9·64
30	0·577	142·5	11·44	11·44

We learn from these experiments that the law according to which the attraction of carbonate of iron increases, is exactly the same as that according to which the repulsion of the calcareous spar increases, and that the respective forces manifest themselves in both cases with the greatest energy in the direction of the optic axis, the attraction along the optic axis being to that across the same axis, in all four cases, as 100 : 71 nearly.

Let us observe for an instant the perfect antithesis which exists between carbonate of lime and carbonate of iron. The former is a diamagnetic crystal. Suspended before the single pole of a magnet, the entire mass is repelled, but the mass in one direction is repelled with peculiar force, and this direction, when the crystal is suspended in the magnetic field, recedes as far as possible

from the poles, and finally sets equatorial. The crystal of carbonate of iron is, on the contrary, strongly magnetic; suspended before a single pole the entire mass is attracted, but in one direction the mass is attracted with peculiar energy, and this direction, when the crystal is suspended in the magnetic field, will approach the poles and finally set axial.

Sulphate of iron in the magnetic field displays a directive action considerably inferior to that of carbonate of iron. Some large crystals were obtained from a chemical manufactory, and from these I cut two clean cubes. Each was suspended by a cocoon fibre in the magnetic field, and the line which stood axial was marked upon it. The white powder which collects by efflorescence around these crystals was washed away, and two transparent cubes remained. These were laid upon the torsion-balance, and instead of the Bristol board used in the last experiment, two plates of glass were placed against the core ends; the adhesion of the cubes, which in delicate experiments of this nature sometimes enters as a disturbing element, was thus reduced to a minimum. As in the case of carbonate of iron, one core only was excited. The cube opposite to this core was first so placed that the line which stood axial in the magnetic field was parallel to the axis of the core; preserving this line horizontal, the three remaining faces were presented successively to the core, and the attraction measured in each particular case; the attractions were as follows:—

Cube of Sulphate of Iron, edges 10 millims.

	Attraction
1st position	43·0
2nd position	36·3
3rd position	40·0
4th position	34·5

[Mean of attraction along axis. 41·5

" " across " 35·4

Or as 100 : 85 nearly.]

From an article translated from Poggendorff's *Annalen*, and published in the June number of the 'Philosophical Magazine,' it will be seen that Professor Plücker has experimented with a cube of sulphate of iron, and has arrived at results which he adduces against the theory of magne-crystallic action advanced by Knoblauch and myself. He rightly concluded that if the position of the crystal, suspended between two poles, were due to the superior attraction exerted in a certain direction, this peculiarity ought to exhibit itself in the attraction of the entire mass of the crystal by the single pole of a magnet. He brings this conclusion to the test of experiment, suspends the crystal from one end of a balance, weighs the attraction in different directions, but finds no such difference as that implied by the conclusion. This result, I believe, is entirely due to the imperfection of his apparatus; I have tried a very fine balance with even worse success than Plücker. Although the torsion-balance furnishes a means of experiment immeasurably firer, still, even with it, great delicacy of manipulation and a considerable exercise of patience are necessary to insure invariable success.

Faraday has discovered, that if a bismuth crystal be suspended in the magnetic field, it will set itself so that a line perpendicular to the plane of most eminent cleavage will be axial; this line he calls the magne-crystallic axis of the crystal. In the memoir by Knoblauch and myself before alluded to, the position of the magne-crystallic axis is affirmed to be a secondary result, depending on the fact that the mass in the direction of the planes of cleavage is most strongly repelled. The general fact of superior repulsion in the direction of the cleavages has been already demonstrated by Faraday.

Our torsion-balance furnishes us with a quantitative confirmation of Faraday's result. Two cubes of bis-

muth were prepared, in each of which the plane of most eminent cleavage formed two of the opposite sides. Suspended by a fibre of cocoon-silk in the magnetic field, the line perpendicular to the cleavage turned into the axial position, or what amounts to the same as far as the eye is concerned, the cleavage itself receded from the poles and stood equatorial. These cubes were placed one on each end of the torsion-balance; first, so that the plane of most eminent cleavage was parallel to the axes of the cores, and afterwards perpendicular to these axes. The respective repulsions are stated in the following tables.

Table IX.—Cubes of Bismuth, edges 6 millims. Plane of most eminent cleavage parallel to axes of cores.

α	T
20	11.7
30	34.8
40	78
45	111
50	153

Table X.—The same cubes. Plane of most eminent cleavage perpendicular to axes of cores.

α	T
20	8
30	23
40	53
45	76.5
50	110

A comparison of these two tables shows us that the repulsion of the cubes, when the plane of most eminent cleavage was parallel to the magnetic axis, is to the repulsion when the said plane was perpendicular thereto, in the ratio nearly of 100 : 71.

What is it, then, which causes this superior manifestation of force in a certain direction? To this question experiment returns the following reply:—‘If the arrangement of the component particles of any body be such as to present different degrees of proximity in different directions, then the line of closest proximity, other circumstances being equal, will be that of strongest attraction in magnetic bodies and of strongest repulsion in diamagnetic bodies.’

The torsion-balance enables us to test this theory. A quantity of bismuth was ground to dust in an agate mortar, gum-water was added, and the mass was kneaded to a stiff paste. This was placed between two glasses and pressed together; from the mass when dried two cubes were taken, the line of compression being perpendicular to two of the faces of each cube and parallel to the other four. Suspended by a silk fibre in the magnetic field, upon closing the circuit the line of compression turned strongly into the equatorial position, exactly as the plane of most eminent cleavage in the case of the crystal. The cubes were placed one upon each end of the torsion-balance; first with the line of compression parallel to the cores, and secondly with the same line perpendicular to the cores. The following are the repulsions exhibited in both cases respectively.

Table XI.—Cubes of powdered Bismuth, edges 7 millims. Line of compression parallel to axes of cores.

α	$\tan \alpha$	T	\sqrt{T}	$8\cdot3 \times \tan \alpha$
30	0·577	22	4·69	4·78
40	0·839	46	6·78	6·96
45	1·000	67	8·19	8·30
50	1·192	98	9·89	9·89

From this table we see that the law of increase for the

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artificial cube is the same as that for diamagnetic substances generally.

Table XII.—The same cubes. Line of compression perpendicular to cores.

<i>a</i>	T
30	13
40	31
45	46
50	67

A comparison of the two tables shows us that the line which stands equatorial in the magnetic field is most strongly repelled upon the torsion-balance, exactly as in the case of the crystal; the repulsion in the direction of this line and in a direction perpendicular to the same being in the ratio of 100 : 66 nearly. Similar experiments were made with cubes of powdered carbonate of iron. The line of compression set axial in the magnetic field, and on the torsion-balance the attraction along this line was a maximum.

[*Summary.*—Differential attractions and repulsions of magnetic and diamagnetic bodies :—

	Along axis	Across axis
Carbonate of iron (attraction)	. . 100 . . .	71
Carbonate of lime (repulsion)	. . 100 . . .	90
Sulphate of iron (attraction)	. . 100 . . .	85
Bismuth (repulsion)	. . . 100 . . .	71
	Along line of pressure	Across line of pressure
Compressed bismuth 100 . . .	66

In all cases in magnetic bodies the line of strongest attraction sets from pole to pole, while in diamagnetic bodies the line of strongest repulsion sets equatorial.]

At the last meeting of the British Association, an ob-

jection, which will probably suggest itself to all who study the subject as profoundly as he has done, was urged, *viva voce*, against this mode of experiment by Sir William Thomson. ‘ You have,’ he said, ‘ reduced the mass to powder, but you have not thereby destroyed the crystalline property ; your powder is a collection of smaller crystals, and the pressing of the mass together gives rise to a predominance of axes in a certain direction ; so that the repulsion and attraction of the line of compression which you refer to the mere closeness of aggregation is, after all, a product of crystalline action.’

I know that this objection, which was specially directed against the experiment made with powdered bismuth and carbonate of lime, floats in the minds of many both in Germany and England, and I am therefore anxious to give it a full and fair reply. I might urge, that in the case of the bismuth powder at least, the tendency of compression would be to place the little component crystals in such a position, that a deportment precisely the reverse of that actually observed might be anticipated. If we pound the crystal to the finest dust, the particles of this dust, to render Thomson’s hypothesis intelligible, must have a certain predominant shape, otherwise there is no reason to suppose that pressure will *always* cause the axes of the little crystals to take up the same predominant direction. Now what shape is most likely here ? The crystal cleaves in one direction more easily than in any other ; is it not then probable that the powder will be chiefly composed of minute scales, whose opposite flat surfaces are the surfaces of principal cleavage ? And what is the most probable effect of compression ? Will it not be to place these little scales with their flat surfaces perpendicular to the line in which the pressure is exerted ? In the crystal, the line perpendicular to the principal cleavage sets axial, and hence it might be expected that the line of compression in

the model would set axial also ; it does not, however,—it sets equatorial.

This, however, though a strong presumptive argument, is not yet convincing ; and it is no easy matter to find one that shall be so. Bismuth powder will remain crystalline, and carbonate of lime is never free from suspicion. I thought I had found an unexceptionable substance in chalk, inasmuch as Ehrenberg has proved it to be a mere collection of microscopic shells ; but Professor Ehrenberg himself informs me, that even these shells, which require a high magnifying power to render them visible, are in their turn composed of infinitesimal crystals of calcareous spar. In this dilemma one way remains open to us : we will allow the objection to stand, and follow it out to its inevitable consequences ; if these are opposed to fact, the objection necessarily falls.

Let us suppose the bismuth powder to be rearranged, so that the perfect crystal from which it was obtained is restored. In this case the axes of all the little component crystals are parallel, they work all together, and hence their action must be greater than if only a majority of them were parallel. In a bismuth *crystal*, therefore, the difference of action in the line of the magne-crystallic axis, and in a line perpendicular thereto, must be a maximum. It must, for example, be greater than any difference which the model of bismuth powder can exhibit ; for a portion of the force attributed to the axes must in this case be annulled by the confused grouping of the little component crystals. In the words of Professor Thomson, it is merely a balance of action brought about by predominance, which can make itself manifest here. Hence, if we measure the repulsion of the crystal in a direction parallel to the principal cleavage, and in a direction perpendicular to it, and also measure the repulsion of the model in the line of compression and in a line perpendicular to it, the ratio of

the two former repulsions, that is, of the first to the second, must be greater than the ratio of the two latter, that is, of the third to the fourth.

Turning to Tables IX. and X., we see that the ratio of the repulsion of the crystal in the direction of principal cleavage to the repulsion in a direction perpendicular to the same is expressed by the fraction $\frac{15}{11} = 1\cdot36$. Turning to Tables XI. and XII., we find that the ratio of the repulsion of the model in the line of compression to the repulsion in a line perpendicular to it is expressed by the fraction $\frac{3}{2} = 1\cdot5$.

In the latter case, therefore, we have the greatest differential effect; which result, were the repulsion due to the mere predominance of axes, as urged by Thomson, would be tantamount to the conclusion that a part is greater than the whole. This result has been entirely unsought. The models were constructed with the view of establishing the general fact, that the repulsion in the line of compression is greatest. That this has fallen out in the manner described is a pure accident. I have no doubt whatever that models might be made in which this difference of action would be double that exhibited by the crystal.

The case, however, is not yet free from suspicion; the gum-water with which it is necessary to bind the powder may possibly exert some secret influence. When isinglass or jelly is compressed, we know that it exhibits optical phenomena similar to those exhibited by crystals; and the squeezing of the metallic dough may induce a kind of crystalline structure on the part of the gum sufficient to produce the phenomena observed.

An experiment to which I was conducted by the following accident will set this doubt, and I believe all other doubts regarding the influence of compression, completely

at rest. Having repeated occasion to refer to the deportment of crystals in the magnetic field, so as to be able to compare this deportment with the attraction or repulsion of the entire mass upon the torsion-balance, through the kindness of Professor Magnus, the great electro-magnet of the University of Berlin¹ was placed in the room where I experimented. One morning a cube of bismuth was suspended between the movable poles, and not knowing the peculiarities of the instrument, I chanced to bring the poles too near each other. On closing the circuit, the principal cleavage of the crystal receded to the equator. Scarcely however was this attained, when the poles were observed moving towards each other, and before I had time to break the circuit, they had rushed together and caught the crystal between them. The pressure exerted squeezed the tube to about three-fourths of its former thickness, and it immediately occurred to me that the theory of proximity, if it were true, ought to tell here. The pressure brought the particles of the crystal in the line of compression more closely together, and hence a modification, if not an entire subversion of the previous action, was to be expected.

Having liberated the crystal, I boiled it in hydrochloric acid, so as to remove any impurity it might have contracted by contact with the iron. It was again suspended between the poles, and completely verified the foregoing anticipation. The line of compression, that is, the magne-crystallic axis of the crystal, which formerly set from pole to pole, now set strongly equatorial. I then brought the poles intentionally near each other, and allowed them to close once more upon the already compressed cube; its original deportment was thereby restored. This I repeated several times with several different crystals, and with the same

¹ A notion of the power of this magnet may be derived from the fact, that the copper helices alone which surrounded the pillars of soft iron weighed 243 pounds.

unvarying result; the line of compression always stood equatorial, and it was a matter of perfect indifference whether this line was the magne-crystallic axis or not. The experiment was then repeated with a common vice. I rubbed the letters from two copper coins with sandstone, and polished the surfaces; between the plates thus obtained various pieces of bismuth were forcibly squeezed; in this way plates were procured about as thick as a shilling, and from half an inch to an inch in length. Although the diamagnetism of the substance tended strongly to cause such a plate, suspended from its edge between the poles, to take up the equatorial position, although the force attributed to the magne-crystallic axis worked in each case in unison with the diamagnetism of the mass, every plate set nevertheless with its length from pole to pole, and its magne-crystallic axis equatorial.

This superior repulsion of the line of compression manifests itself upon the torsion-balance also. The cubes of bismuth crystal already made use of were squeezed in a vice to about four-fifths of their former thickness; the line of compression in each case being perpendicular to the principal cleavage, and consequently parallel to the magne-crystallic axis. From the masses thus deformed, two new cubes were taken; these laid upon the torsion-balance in the positions indicated in the tables, gave the following results:—

Table XIII.—Bismuth Crystals, compressed cubes. Plane of most eminent cleavage parallel to axes of magnets.

α	T
20	7·8
30	21
40	47
45	67
50	101

Table XIV.—The same cubes. Plane of most eminent cleavage perpendicular to axes of magnets.

<i>a</i>	T
20	9
30	25.5
40	57.3
45	79
50	113

Looking back to Tables IX. and X., we see that the line which was there repelled most strongly is here repelled most feebly, and *vice versa*, the change being due to compression. The ratio there is 100 : 71 ; here it is 100 : 112 nearly.

I have been careful to make similar experiments with substances concerning whose amorphism there can be but little doubt. A very convenient substance for showing the influence of compression is the white wax used in candles. The substance is diamagnetic. A little cylinder of the wax suspended in the magnetic field set with its axis equatorial. It was then placed between two stout pieces of glass and squeezed as thin as a sixpence ; suspended from its edge, the plate thus formed set its length, which coincided with the axis of the previous cylinder, axial, and its shortest dimension equatorial.

The plate was then cut into little squares, which were laid one upon the other and pressed together to a compact cubical mass. Two such cubes were placed upon the torsion-balance, and the repulsion in the line of compression, and in a line perpendicular to the same, were determined—the former was considerably the greater.

The crumb, scooped from a fresh roll, was placed between the glass plates, and squeezed closely together ; after remaining in the vice for half an hour, a rectangle was taken from the plate thus formed, and suspended from its edge in

the magnetic field ; it set like a magnetic body, with its length from pole to pole. The mass was diamagnetic, its line of compression was repelled, and an apparent attraction of the plate was the consequence.

Fine wheat-flour was mixed with distilled water into a stiff paste, and the diamagnetic mass was squeezed into thin cakes. The cakes when suspended from the edges set always with their longest dimension from pole to pole, the line of compression being equatorial.

Rye-flour, from which the Germans make their black bread, was treated in the same manner and with the same result.

I have an oblong plate of shale from the neighbourhood of Blackburn in Lancashire, which imitates M. Plücker's first experiment with tourmaline with perfect exactitude. The mass is magnetic, like the tourmaline. Suspended from the centre of one of its edges, it sets *axial* ; this corresponds to the position of the tourmaline when the optic axis is vertical. Suspended from the centre of the adjacent edge, it sets even more strongly *equatorial* ; this corresponds with the tourmaline when the optic axis is horizontal. If the eyes be closed, and the respective positions of the plate of shale ascertained by means of touch, and if the same be done with Plücker's plate of tourmaline, it will be impossible to distinguish the one deportment from the other.

With regard to the experiment with the cherry-tree bark, I have a bar of chemically pure bismuth which does not contain a trace of magnetism, and which exhibits the precise phenomena observed with the bark. These phenomena do not therefore necessitate the hypothesis of two conflicting forces, the one or the other of which predominates according as the poles of the magnet are more or less distant. I have already commenced an investigation in which the deportment of the bark and other phenomena of an analogous nature will be more fully discussed.

Every inquirer who has occupied himself experimentally with electro-magnetic attractions must have been struck with the great and speedy diminution of the force by which soft iron is attracted, when the distance is augmented, in the immediate neighbourhood of the poles. In experiments with spheres of soft iron, I have usually found that a distance of $\frac{1}{10}$ th of an inch between the sphere and the magnet is sufficient to reduce the force with which the former is attracted to $\frac{1}{10}$ th of the attraction exerted when the sphere is in contact. To any one acquainted with this fact, and aware, at the same time, of the comparative sluggishness with which a bismuth ball moves in obedience to the repulsive force even when close to the poles, a law the exact reverse of that affirmed by Plücker must appear exceedingly probable.

The bismuth balls were placed upon the torsion balance ; on the top of one of them a particle of iron filing was fixed, and with this compound mass the space opposite to a core excited by a current of 50° was sounded. The beam was brought by gentle pushing into various positions, sometimes close to the magnet, sometimes distant. The position of equilibrium for the beam when the core was unexcited was always zero. When the beam was pushed to a distance of 4° (about $\frac{3}{10}$ ths of an inch) from the core end, on exciting the magnet it receded still further and rested against a stop at 9° distant. When the current was interrupted the beam left the stop and approached the core ; but if, before it had attained the third or fourth degree, the circuit was closed, the beam was driven back and rested against the stop as before.

Preserving the current constant at 50° , the index of the torsion-head was turned gently against the repulsion, and in this way the ball was caused slowly to approach the magnet. The repulsion continued until the glass fibre of the beam pointed to 2° ; here an *attractive* force suddenly

manifested itself, the ball passed speedily on to contact with the core end, to separate it from which a torsion of 50° was requisite.

The circuit was broken and the beam allowed to come to rest at zero, a space of about $\frac{1}{12}$ th of an inch intervening between the ball and the end of the magnet; on closing the circuit the beam was *attracted*. The current was once more interrupted, and the torsion-head so arranged, that the beam came to rest at 3° distant; on establishing the current again the beam was *repelled*. Between 0° and 3° there was a position of unstable equilibrium for the beam; from this place to the end of the magnet attraction was triumphant, beyond this place repulsion prevailed.

Here we see, that on approaching the pole, the attraction of the magnetic particle mounts much more speedily than the repulsion of the diamagnetic ball; a result the reverse of that arrived at by the learned Professor, but most certainly coincident with what everybody who has closely studied electro-magnetic attractions would expect. Shall we therefore conclude that 'magnetism' increases more quickly than 'diamagnetism'? The experiment by no means justifies so wide a generalisation. If magnetism be limited to the attraction of soft iron, then the above conclusion would be correct; but it is not so limited. Plücker calls the attraction of his watch-glass magnetism, the attraction of a salt of iron bears the same name, and it so happens that the attraction of a salt of iron on approaching the poles increases incomparably more slowly than the attraction of iron itself. The proof of this remarkable fact I will now proceed to furnish.

From one end of a very fine balance a sphere of soft iron, $\frac{1}{12}$ th of an inch in diameter was suspended. Underneath, and about $\frac{1}{12}$ th of an inch distant from the ball when the balance stood horizontal, was the flat end of a straight

electro-magnet. On sending a current of 30° through the surrounding helix, the ball was attracted, and the force necessary to effect a separation was measured : it amounted to 90 grammes. A plate of thin window-glass was then placed upon the end of the magnet, and the ball allowed to rest upon it. The weight necessary to effect a separation, when the magnet was excited by the same current, amounted to 1 gramme. Here an interval of about $\frac{1}{15}$ th of an inch was sufficient to reduce the attractive force to $\frac{1}{90}$ th of that exerted in the case of contact.

A sphere of sulphate of iron, of somewhat greater diameter than the iron ball, was laid upon one end of the torsion-balance ; the adjacent core was excited by a current of 30° , and the force necessary to effect a separation of the core from the sphere was determined : it amounted to 20° of torsion. The plate of glass used in the last experiment was placed against the core end, and the force necessary to effect a separation from it, with a current of 30° , was also determined. The difference, which in the case of the soft iron amounted to $\frac{89}{90}$ ths of the primitive attraction, was here scarcely appreciable. At a distance of $\frac{1}{15}$ th of an inch the sphere of sulphate of iron was almost as strongly attracted as when in immediate contact.

Similar experiments were made with a pellet of carbonate of iron, and with the same result. At a distance of $\frac{1}{7}$ th of an inch the attraction was two-thirds of that exerted in the case of contact. An interval of $\frac{1}{1000}$ th of an inch is more than sufficient to effect a proportionate diminution in the case of soft iron.

A salt of iron in the immediate neighbourhood of the poles behaves like iron itself at a considerable distance, and the deportment of bismuth is exactly similar. A slight change of position will make no great difference of attraction in the one case or of repulsion in the other.

To make the antithesis between magnetism and diamagnetism perfect, we require a yet undiscovered metal, which shall bear the same relation to bismuth, antimony, sulphur, &c., which iron does to a salt of iron. Whether nature has such a metal in store for the enterprising physicist, is a problem on which I will hazard no conjecture.

PRINCIPAL RESULTS OF THE FOREGOING INVESTIGATION.

1. *The repulsion of a diamagnetic substance placed at a fixed distance from the pole of a magnet is governed by the same law as the attraction of a magnetic substance.*
2. *The entire mass of a magnetic substance is most strongly attracted when the attracting force acts parallel to that line which sets axial when the substance is suspended in the magnetic field; and the entire mass of a diamagnetic substance is most strongly repelled when the repulsion acts parallel to the line which sets equatorial in the magnetic field.*
3. *The superior attraction and repulsion of the mass in a particular direction is due to the fact, that in this direction the material particles are ranged more closely together than in other directions; the force exerted being attractive or repulsive according as the particles are magnetic or diamagnetic. This is a law applicable to matter in general, the phenomena exhibited by crystals in the magnetic field being particular manifestations of the same.*

BERLIN: June, 1851.

ADDITIONS AND REMARKS, 1870.

Poisson's prediction of Magne-crystallic action.

In March 1851, Professor, now Sir William Thomson, drew attention to an exceedingly remarkable instance of theoretic foresight on the part of Poisson, with reference to the possibility of magne-crystallic action.

'Poisson,' says Sir William, 'in his mathematical theory of magnetic induction, founded on the hypothesis of magnetic fluids, "moving within the infinitely small magnetic elements," of which he assumes magnetisable matter to be constituted, does not overlook the possibility of those magnetic elements being non-spherical and symmetrically arranged in crystalline matter, and he remarks that a finite spherical portion of such a substance would, when in the neighbourhood of a magnet, act differently according to the different positions into which it might be turned with its centre fixed. But "such a circumstance not having yet been observed," he excludes the consideration of the structure which would lead to it from his researches, and confines himself in his theory of magnetic induction to the case of matter consisting either of spherical magnetic elements or of non-symmetrically disposed elements of any forms. Now, however, when a recent discovery of Plücker's has established the very circumstance, the observation of which was wanting to induce Poisson to enter upon a full treatment of the subject, the importance of working out a magnetical theory of magnetic induction is obvious.'

Sir William Thomson then proceeds to make the necessary 'extension of Poisson's mathematical theory of magnetic induction'; and he publishes the following striking quotation:—

'La forme des éléments pourra aussi influer sur cette

intensité ; et cette influence aura cela de particulier, qu'elle ne sera pas la même en des sens différens. Supposons, par exemple, que les élémens magnétiques sont des ellipsoïdes dont les axes ont la même direction dans toute l'étendue d'un même corps, et que ce corps est une sphère aimantée par influence, dans laquelle la force coercitive est nulle ; les attractions ou répulsions qu'elle exercera au dehors seront différentes dans le sens des axes de ces élémens et dans tout autre sens ; en sorte que si l'on fait tourner cette sphère sur elle-même, son action sur un même point changera, en général, en grandeur et en direction. Mais si les élémens magnétiques sont des sphères de diamètres égaux ou inégaux, ou bien s'ils écartent de la forme sphérique, mais qu'ils soient disposés sans aucune régularité dans l'intérieur d'un corps aimanté par influence, leur forme n'influera plus sur les résultats, qui dépendront seulement de la somme de leurs volumes, comparée au volume entier de ce corps, et qui seront alors les mêmes en tout sens. Ce dernier cas est celui du fer forgé, et sans doute aussi des autres corps non cristallisés dans lesquels on a observé le magnétisme. Mais il serait curieux de chercher si le premier cas n'aurait pas lieu lorsque ces substances sont cristallisées ; on pourrait s'assurer par l'expérience soit en approchant un cristal d'une aiguille aimantée, librement suspendue, soit en faisant osciller de petites aiguilles taillées dans des cristaux en toute sorte de sens, et soumises à l'action d'un très-fort aimant.' (Mém. de l'Institut, 1821-22. Paris, 1826.)

Subsequent to the foregoing inquiries, I had a powerful and delicate torsion-balance constructed for me by Mr. Becker, and in the autumn of 1855, I examined with it the differential attractions and repulsions of large additional number of crystals and compressed substances.

Dichroite was one of the crystals then examined. It was magnetic. The form was a cube with two pairs of

faces parallel to the crystallographic axis, and one pair perpendicular to it. The crystal was found to possess three magnetic axes of unequal values. Measured twice in each case by the torsion-balance the attraction of the mass along the three axes respectively was—

	Least axis	Middle axis	Greatest axis
	222	293	300
	225	288	300
Mean . . .	223.5	290.5	300

When the crystal was suspended from its centre of gravity with the least and greatest axes horizontal, the rapidity of its vibration was greater than when the intermediate axis was pitted against either of the two others. Depending as it did upon the differential induction, the rate of vibration ought of course to be highest where the difference is greatest.

Various other crystals possessing three magnetic axes were examined at the time here referred to. The deportment when suspended from their centres of gravity in the magnetic field was always in harmony with the differential attractions and repulsions of the mass as measured by the torsion-balance. Numerous compressed substances were also examined, and their deportment on the torsion-balance compared with their deportment in the magnetic field. As far as the experiments extended the harmony observed in the case of crystals was exhibited here also.

It would give me great pleasure to go again over the ground traversed in the preceding papers. The experiments, I think, are secure; but I should like to review the molecular theory of the whole subject, and examine still further the remarkable variations of magnetic capacity produced by mechanical strains and pressures. In 1855 a great number of experiments were made on compressed powders, but I was deflected from the subject immediately afterwards, and from 1856 to the present time I have

been unable to bestow any attention on the subject of diamagnetism. A rich reward is probably here in store for the young investigator.

In the foregoing pages, the mutual inductive action of the particles of carbonate of iron is referred to. Their shape ought also to be taken into account. From a long list of experiments I will take one which bears upon this point.

Pure white wax is strongly diamagnetic. When squeezed between clean plates it always sets the line of compression equatorial in the magnetic field.

A crystal of pure carbonate of iron was pounded to an extremely fine powder in a mortar. The finger and thumb were dipped into the mixture, and the powder adhering to them was in great part brushed away by mutual friction. The minute residue was mixed with a quantity of white wax. The mass was then squeezed; square plates were taken from the flattened mass, and laid one upon another to form a cube. Suspended in the magnetic field it set the line of compression axial.

When the smallness of the quantity of magnetic powder here employed and its extremely sparse diffusion in the mass of the wax are taken into consideration, it can hardly be supposed that the setting of the line of compression axial was due to the mutual induction of the particles. It is, perhaps, more probable that the pressure brought the axes of the minute crystals composing the dust into partial parallelism with the line of compression. This would be the natural result of the shape of the particles. The longest dimension would tend to set perpendicular to the direction of pressure, and this, in the particular case before us, would bring the direction of maximum magnetisation parallel to the same line. The surmise of Sir William Thomson may, in this case, be justified.

But though this action may occur in the case of

carbonate of iron, it fails in its application to compressed bismuth crystals. There is nothing in the structure of the crystal to warrant the notion that the effect of compression is merely to re-arrange the particles. *By mechanical pressure a new magnetic capacity is here superinduced.*

Three other cubes were formed of the wax in the manner above described, the wax being kneaded in the three respective cases with increasing quantities of the carbonate of iron. The mixture was then compressed, and it was found that the adherence of the line of compression to the line joining the poles became stronger as the quantity of the carbonate of iron dust was increased.

But now a curious effect is to be mentioned which needs further examination. A quantity of very fine oxide of iron was mixed with the powder of the carbonate, and the smallest pinch of the mixture was kneaded into a lump of wax. Cubes were formed of the substance in the usual manner. But while the pure carbonate always caused the line of compression to set axial; the admixture of the oxide entirely changed this deportment, and caused the direction of pressure to set equatorial.

Three other cubes were formed containing gradually increasing quantities of the oxide. In all cases the line of compression set equatorial.

A class of results of which this is a type was forced on my attention by the anomalous behaviour of the carbonate of iron in certain cases. The line of compression sometimes sets axial, sometimes equatorial; the discrepancies being finally traced to the oxide which adhered here and there as a crust to the pure crystal. A great number of different powders were thus examined; and indeed, iron itself was reduced to powder in various ways. The greatest difficulty in these experiments arose from the fact that in strongly magnetic substances the slightest elongation of

the particle was sufficient to determine its position. The coercive force of all magnetic powders was also a source of confusion and difficulty.

At the time here referred to I also tried various experiments with a view of connecting calorific conduction with magnetic induction. Heat and magnetism do not seem to be operated upon equally by molecular arrangement. By a beautiful and simple mode of experiment, de Senarmont has shown that crystals conduct heat differently in different directions, and one of the best examples of this difference is furnished by rock-crystal. Coating a plate of the substance with wax, and passing through the plate a heated wire, the heat communicated to the crystal melts the wax into an oval, the longest axis of which is parallel to the axis of the crystal.¹ As regards heat the differential action is specially striking, but hardly any crystal is more inactive than quartz in the magnetic field. Hence the state of the ether, or of the molecules, which produces great differences as regards calorific conduction, may produce no sensible difference as regards magnetic induction. Sulphate of baryta has, according to de Senarmont, sensibly the same calorific conductivity in all directions; but it has three unequal axes of magnetic induction; two parallel to the two diagonals of the base, and an intermediate one parallel to the axis of the prism.

The ratio of the two axes of the ellipse in rock-crystal is as 131 : 100; while in calcite, which is far more energetic in the magnetic field, the ratio is only as 111 : 100. In calcite, moreover, the direction of greatest calorific conduction is also that of highest diamagnetic induction, while in selenite the case is reversed. In transparent tourmaline the direction of minimum calorific conduction is parallel to the axis; this, at all events in coloured magnetic crystals, is the

¹ *Annales de Chimie et de Physique*, vol. xxi. p. 457, also vol. xxii. *Heat as a Mode of Motion*, 3rd edition, page 202.

direction of maximum magnetic induction. De Senarmont says, 'It is remarkable to observe that quartz, the optical constants of which differ little among themselves, compared with those of calc-spar, possesses on the contrary conductibilities which differ far more than those of the spar.'¹ The magnetic deportment of quartz is more analogous to its optical than to its calorific deportment. A similar remark applies to selenite. As soon as I can command the necessary time, I shall examine whether there is any general relation here.

¹ *Annales de Chimie et de Physique*, vol. xxviii. p. 279.

POLARITY OF THE DIAMAGNETIC FORCE.

Introduction, 1870.

SOON after the discovery of diamagnetism, Professor Reich, of Freiburg, made the following very important experiment. Placing a ball of bismuth on a torsion-balance which had been previously employed in determinations of the density of the earth, he found that ‘magnet bars, on being brought up in a horizontal direction to the case near the ball, produced a very distinct repulsion, both when the north and the south pole were brought near. But when several similar bars were brought near, half with their north and the other half with their south poles, there was no effect perceptible, or merely a slight one arising from the inequality of the magnets employed.’¹ Prof. W. Weber² immediately saw the bearing of this result on the character of diamagnetism. ‘From this single experiment,’ he says, ‘it might be concluded with the greatest probability that the origin of the diamagnetic force is not to be sought for in the never-changing metallic particles of the bismuth, but in an imponderable constituent moving between them, which on the approach of the pole of a magnet is displaced and distributed differently according to the character of this pole.’ He then inquires into the nature of this imponderable constituent, and into its bearing on the view first enunciated by Faraday, that dia-

¹ Poggendorff's *Annalen*, vol. lxxiii. p. 60; Phil. Mag. vol. xxxiv. p. 127.

² Poggendorff's *Annalen*, January 7, 1848; Taylor's *Scientific Memoirs*, vol. v. p. 477.

magnetism might be explained by assuming the existence of a polarity the reverse of that of magnetism. He subjects the view to an experimental test, and shows that a bar of bismuth which at a certain distance had no sensible action on a magnetic needle, did exert an action on the same needle when placed between the poles of a powerful magnet.¹ ‘Between the two poles of the horseshoe magnet,’ writes Weber, ‘a very perceptible and measurable effect is exhibited, viz., a deflection of the needle, owing to one pole being repelled and the other attracted.’ He found that when the poles of the influencing magnet were reversed, the deflection produced by the bismuth was reversed also; and that when a piece of iron was substituted for the bismuth, the deflection produced by the magnetic metal was opposite to that produced by the diamagnetic one. Hence he concluded that Faraday’s hypothesis was proved. To render the proof more complete, Weber made an exceedingly skilful arrangement to show that induced currents were excited by the diamagnetisation of bismuth as well as by the magnetisation of iron. The proof of diamagnetic polarity appeared, therefore, to be complete.

Faraday, however, again took up the subject. Referring to his hypothesis of diamagnetic polarity, he says the view was ‘received so favourably by Plücker, Reich, and others, but above all by W. Weber, that I had great hope it would be confirmed; and though certain experiments of my own did not increase that hope, still my desire and expectation were in that direction.’ ‘It appeared to me,’ he continues, ‘that many of the results which have been supposed to indicate a polar condition, were only consequences of the law that diamagnetic bodies tend to go from stronger to weaker places of magnetic

¹ The action of the magnetic poles upon the suspended needle was neutralised by a second magnet, the needle being thus rendered sufficiently sensitive to respond to the action of the bismuth.

action.' In a paper of great experimental power, he demonstrates that the induced currents ascribed by Weber to the diamagnetisation of bismuth were probably due to a totally different cause; and with regard to Weber's experiment with the bar of bismuth placed between the poles of a magnet, Faraday says, 'I have repeated this experiment most anxiously and carefully, but have never obtained the slightest trace of action with the bismuth. I have obtained action with the iron; but in those cases the action was far less than if the iron were applied outside, between the horseshoe magnet and the needle, or to the needle alone, the magnets being entirely away. On using a garnet, or a weak diamagnetic substance of any kind, I cannot find that the arrangement is at all comparable, for readiness of indication or delicacy, with the use of a common or an astatic needle, and therefore I do not understand how it could become a test of the polarity of bismuth when these fail to show it.'

'Finally,' he continues, 'I am obliged to say that I can find no experimental evidence to support the hypothetical view of diamagnetic polarity, either in my own experiments, or in the repetition of those of Weber, Reich, or others. I do not say that such a polarity does not exist, and I should think it possible that Weber, by far more delicate apparatus than mine, had obtained a trace of it, were it not that then also he would have certainly met with the far more powerful effects produced by copper, gold, silver, and the better conducting diamagnetics.'

In a very exhaustive and beautiful memoir translated by myself from Poggendorff's *Annalen*, vol. lxxvii., p. 145,¹ Professor Weber returns to the subject of dia-

¹ *Scientific Memoirs*, published by Taylor & Francis, New Series, vol. i. p. 163.

magnetism, and considers four possible assumptions to account for the origin of the diamagnetic effects :—

1. The internal cause of such effects may be referred to the existence of two magnetic fluids which are more or less independent of the ponderable matter which carries them.
2. They may be due to the existence of two magnetic fluids, which are only capable of moving in connexion with their ponderable carriers (rotatory molecular magnets).
3. They may be due to the existence of permanent molecular currents formed by the electric fluids, and which rotate with the molecules.
4. They may be due to the existence of electric fluids, which can be thrown into molecular currents.

Weber decides in favour of the fourth hypothesis. He supposes that by the act of magnetisation molecular currents are *generated* in diamagnetic bodies ; which currents, like those of Faraday, have a direction opposed to that of their generators. But Faraday's currents are of vanishing duration, being immediately extinguished by the resistance of the conductors through which they move. Diamagnetism, however, would require *permanent* molecular currents to account for it. Weber secures this permanence by supposing that the induced molecular currents move *in channels of no resistance*¹ round the molecules. This assumption enables him to link all the phenomena of diamagnetism together in a satisfactory manner. While recognising the extreme beauty of the hypothesis, I should hesitate to express a belief in its truth.

Weber also again applied his wonderful experimental skill to the subject of currents induced by the act of

¹ This, indeed, is involved in Ampère's theory of molecular currents. See Letter of Prof. Weber further on.

diamagnetisation; and in my opinion, fairly met all the requirements of the case; but neither his labours nor those of Poggendorff and Plücker produced conviction in the mind of Faraday. The notion of a distinct diamagnetic polarity was also opposed by others. Prof. von Feilitzsch, for example, contended, on theoretic grounds, and backed his contention by definite experiments, that the magnetic excitement of bismuth and of iron were one and the same. This was also the view of M. Becquerel. Matteucci subsequently entered the field as an ardent opponent of diamagnetic polarity.

The investigations recorded in the Third, Fourth, Fifth, and Sixth Memoirs, but mainly in the three last, are directed to the complete clearing up of this subject.

THIRD MEMOIR.

ON THE POLARITY OF BISMUTH, INCLUDING AN EXAMINATION OF THE MAGNETIC FIELD.¹

THE polarity of bismuth is a subject on which philosophers have differed and on which they continue to differ. On the one side we have Weber, Poggendorff, and Plücker, each affirming that he has established this polarity ; on the other side we have Faraday, not affirming the opposite, but appealing to an investigation which is certainly calculated to modify whatever conviction the results of the above-named experimenters might have created. It will probably have occurred to those occupied experimentally with diamagnetic action that, whenever the simple mode of permitting the body experimented with to rotate round an axis passing through its own centre of gravity, can be applied, it is preferable in point of delicacy to all others. A crystal of calcareous spar, for example, when suspended from a fine fibre between the poles, readily exhibits its directive action, even in a field of weak power ; while to establish that peculiar repulsion of the mass which is the cause of the directive action, even with high power and with the finest torsion-balance, is a matter of considerable difficulty. In the knowledge of this and in the fact of my having a piece of bismuth, whose peculiar structure suggested the possibility of submitting the question of diamagnetic polarity to a new test, the present brief inquiry originated.

¹ Phil. Mag., Nov. 1851.

In December 1847 a paper on 'Diamagnetic Polarity' was read before the Academy of Sciences in Berlin by Professor Poggendorff, the result arrived at by the writer being, that a bismuth bar, suspended horizontally and occupying the equatorial position between two excited magnetic poles, was transversely magnetic—that side of the bar which faced the north pole possessing north polarity, and that side which faced the south pole possessing south polarity; the excitation being thus the opposite of that of iron, and in harmony with the original conjecture of Faraday.

The method adopted by Poggendorff was as follows:—The bismuth bar was suspended within a helix of copper wire, the coils of which were perpendicular to the axis of the bar. The helix was placed between the opposite poles of a magnet, so that the axis of the helix was perpendicular to the line joining the poles. The bismuth took up the usual equatorial position, its length thus coinciding with the axis of the helix. On sending an electric current through the latter the bar was weakly deflected in a certain direction, and on reversing the current, a feeble deflection in the opposite direction was observed. The deflection was such as must follow from the supposition, that the north pole of the magnet had excited a north pole in the bismuth, and the south pole of the magnet a south pole.

It will be at once seen that a considerable mechanical disadvantage was connected with the fact that the distance from pole to pole of the transverse magnet was very short, being merely the diameter of the bar. If a piece of bismuth, instead of setting equatorial, could be caused to set axial, a mechanical couple of far greater power would be presented to the action of the surrounding current. Now it is well known that bismuth sets in the magnetic field with the plane of most eminent cleavage equatorial:

§6 DIAMAGNETISM AND MAGNE-CRYSTALLIC ACTION.

hence, if a bar of bismuth could be obtained with the said plane of cleavage perpendicular to its length, the directive power of such a bar might be sufficient to overcome the tendency of its ends to proceed from stronger to weaker places of magnetic action and to set the bar axial. After repeated trials of melting and cooling in the laboratory of Professor Magnus in Berlin, I succeeded in obtaining a plate of this metal in which the plane of most eminent cleavage was perpendicular to the flat surface of the plate, and perfectly parallel to itself throughout. From this plate a little cylinder, an inch long and 0·2 of an inch in diameter, was cut, which being suspended horizontally between the excited poles, turned strongly into the axial position, thus behaving to all appearance as a bar of iron.

About 100 feet of copper wire overspun with silk were wound into a helix so that the cylinder was able to swing freely within it. Through a little gap in the side of the helix a fine silk fibre descended, to which the bar was attached; to prevent the action of the bar from being disturbed by casual contact with the little fibrous ends protruding from the silk, a coating of thin paper was gummed to the interior.

The helix was placed between the flat poles of an electro-magnet, so that the direction of its coils was from pole to pole. It being first ascertained that the bar moved without impediment, and that it hung perfectly horizontal, the magnet was excited by two of Bunsen's cells; the bar was immediately pulled into the axial line, being in this position parallel to the surrounding coils. A current from a battery of six cells was sent through the helix, so that the direction of the current, *in the upper half of the helix*, was from the south pole to the north pole of the magnet. The cylinder, which an instant before was motionless, was deflected, forming at the limit of its swing an angle of 70° with its former position; the

final position of equilibrium for the bar was at an angle of 35° , or thereabouts, with the axial line.

Looking from the south pole towards the north pole of the magnet, or in the direction of the current as it passed over the bar, that end of the bar which faced the south pole swung to the left.

The current through the helix being interrupted and the bar brought once more to rest in the axial position (which of course is greatly facilitated by the proper opening and closing of the circuit), a current was sent through in the opposite direction, that is from the north pole to the south ; the end of the bar, which in the former experiment was deflected to the left, was now deflected an equal quantity to the right. I have repeated this experiment a great number of times and on many different days with the same result.

In this case the direction of the current by which the magnet was excited was constant, that passing through the helix which surrounded the bismuth cylinder being variable. The same phenomena are exhibited if we preserve the latter constant and reverse the former.

A polar action seems undoubtedly to be indicated here ; but if a polarity be inferred, it must be assumed that the north pole of the magnet excites a south pole in the bismuth, and the south pole of the magnet a north pole in the bismuth ; for by reference to the direction of the current and the concomitant deflection, it will be seen that the deportment of the bismuth is exactly the same as that which a magnetised needle freely suspended between the poles must exhibit under the same circumstances.

The bar of bismuth was then removed, and a little bar of magnetic shale was suspended in its stead ; it set axial. On sending a current through the surrounding helix, it was deflected in the same manner as the bismuth. The piece of shale was then removed and a little bar of iron was sus-

pended within the helix; the residual magnetism which remained in the cores after the cessation of the exciting current was sufficient to set the bar axial; a very feeble current was sent through the helix and the deflection observed—it was exactly the same as that of the bismuth and the shale.

These results being different from those obtained by M. Poggendorff, I repeated his experiment with all possible care. A bar of ordinary bismuth, an inch in length and about 0·2 of an inch in diameter, was suspended within the helix; on exciting the magnet, it receded to the equator, and became finally steady there. The axis of the bar thus coincided with the axis of the helix. A current being sent through the latter, the bar was distinctly deflected. Supposing an observer to stand before the magnet, with the north pole to his right and the south pole to his left, then when a current passed through the upper half of the coil from the north to the south pole, that end of the bismuth which was turned towards the observer was deflected towards the north pole; and on reversing the current, the same end was deflected towards the south pole. This seems entirely to agree with the former experiment. When the bar hung equatorially between the excited poles, on the supposition of polarity the opposite ends of all its horizontal diameters were oppositely polarised. Fixing our attention on one of these diameters, and supposing that end which faced the north pole of the magnet to be gifted with south polarity, and the end which faced the south pole endowed with north polarity, we see that the deportment to be inferred from this assumption is the same as that actually exhibited; for the deflection of *a polarised diameter* in the same sense as a magnetic needle, is equivalent to the motion of *the end of the bar* observed in the experiment.

The following test, however, appears to be more refined

than any heretofore applied. Hitherto we have supposed the helix so placed between the poles that the direction of its coils was parallel to the line which united them ; let us now suppose it turned 90° round, so that the axis of the helix and the line joining the poles may coincide. In this position the planes of the coils are parallel to the planes in which, according to the theory of Ampère, the molecular currents of the magnet must be supposed to move ; and we have it in our power to send a current through the helix in the same direction as these molecular currents, or in a direction opposed to them. Supposing the bar first experimented with suspended within the coil, and occupying the axial position between the excited poles, a current in the helix opposed to the molecular currents of the magnet will, according to the views of the German philosophers named at the commencement, be in the same direction as the currents evoked in the bismuth : hence such a current ought to exert no deflecting influence upon the bar ; its tendency, on the contrary, must be to make the bar more rigid in the axial position. A current, on the contrary, whose direction is the same as that of the molecular currents in the magnet, will be opposed to those evoked in the bismuth ; and hence, under the influence of such a current, the bar ought to be deflected.

The bar first experimented with was suspended freely within the helix, and permitted to come to rest in the axial position. A current was sent through the helix in the same direction as the molecular currents of the magnet, but not the slightest deflection of the bar was perceptible ; when, however, the current was sent through in the opposite direction, a very distinct deflection was the consequence : by interrupting the current whenever the bar reached the limit of its swing, and closing it when the bar crossed the axial line, the action could be increased to such a degree as to cause the bar to make an entire

rotation round the axis of suspension. This result is diametrically opposed to the above conclusion [as to diamagnetic polarity]—here again the bismuth bar behaves like a bar of iron.

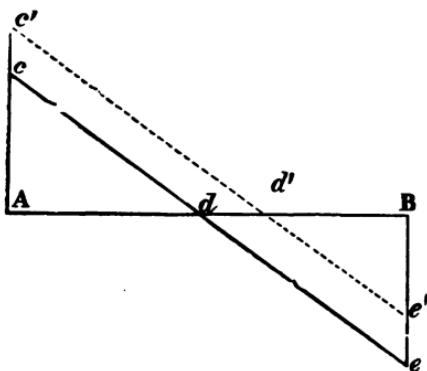
These experiments seem fully to bear out the theory advanced by von Feilitzsch in his letter to Faraday.¹ He endeavours to account for diamagnetic action on the hypothesis that its polarity is the same as that of iron; ‘only with this difference, that in a bar of magnetic substance the intensity of the distribution over the molecules *increases* from the ends to the middle, while in a bar of diamagnetic substance it *decreases* from the ends to the middle.’ So far as I can see, however, the reasoning of von Feilitzsch necessitates the assumption, that in the self-same molecule the poles are of unequal values, that the intensity of the one is greater than that of the other, an assumption which will find some difficulty of access into the speculations of most physicists. A peculiar *directive* action might be readily brought about by the distribution of magnetism assumed by von Feilitzsch; but up to the present time I see no way of reconciling the repulsion of the total mass of a piece of bismuth with the idea of a polarity similar to that of iron.

During these inquiries, an observation of Faraday perpetually recurred to me. ‘It appeared to me,’ he writes,² ‘that many of the results which had been supposed to indicate a polar condition were only consequences of the law that diamagnetic bodies tend to go from stronger towards weaker places of action.’ The question here arose, whether the various actions observed might not be explained by reference to the change effected in the magnetic field when it is intersected by an electric current. The distribution of magnetic intensity between the poles will perhaps be rendered most clear by means of a diagram. Let A B

¹ Phil. Mag., S. 4, vol. i. p. 46. ² Phil. Mag., S. 3, vol. xxxvii. p. 89.

represent the distance between the polar faces; plotting the intensity at every point in A B as an ordinate from that point, the line which unites the ends of all these ordinates will express the magnetic distribution. Suppose this line to be cde . Commencing at A , the intensity of attraction towards this face decreases as we approach the centre d , and at this point it is equilibrated by the equal and opposite attraction towards B . Beyond d the residual attraction towards A becomes negative, that is, it is now in the direction of B . The point d will be a position of stable equilibrium for a diamagnetic sphere, and of unstable

FIG. 1.



equilibrium for a magnetic sphere. But if, through the introduction of some extraneous agency, the line of distribution be shifted, say to $c'd'e'$, the point will be no longer a position of equilibrium; the diamagnetic sphere will move from this point to d' , and the magnetic sphere will move to the pole A .

For the purpose of investigating whether any change of this nature takes place in the magnetic field when an electric current passes through it, I attached a small sphere of carbonate of iron to the end of a slender beam of light wood; and balancing it by a little copper weight fixed to the other end, suspended the beam horizontally from a silk

fibre. Attaching the fibre to a movable point of suspension, the little sphere could be caused to dip into the interior of the helix as it stood between the poles, and to traverse the magnetic field as a kind of feeler. The law of its action being that it passes from weaker to stronger places of force, we have in it a ready and simple means of testing the relative force of various points of action. The point of the beam to which the fibre was attached being cut by the axis of the helix produced, and the sphere being also on the same level with the axis, when the magnet was excited¹ it passed into the position occupied by the *defined* line in

FIG. 2.

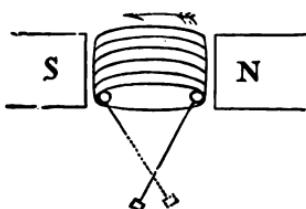


fig. 2, thus resting against the interior of the helix a little within its edge. On sending a current through the helix, which in the upper half thereof had the direction of the arrow, the sphere loosed from its position, sailed gently across the field, and came to rest in the

position of the dotted line. If, while thus sailing, the direction of the current in the helix, or of the current by which the magnet was excited, were reversed, the sphere was arrested in its course and brought back to its original position. In like manner, when the position of the sphere between the poles was that of the dotted line, a current sent through the helix in a direction opposed to the arrow, caused the sphere to pass over into the position of the defined line.

The sphere was next introduced within the opposite edge of the helix (fig. 3). On exciting the magnet, the beam came to rest in the position of the defined line; on

¹ One of Bunsen's cells was found sufficient; when the magnetic power was high, the change caused by the current was not sufficient to deflect the beam.

sending a current through the helix in the direction of the arrow, the sphere loosed, moved towards the north pole, and came to rest in the dotted position. If while in this position either the current of the magnet or the current of the helix were reversed, the sphere went back ; if both were reversed simultaneously, the sphere stood still.

From these facts we learn, that if the magnetic field be divided into four compartments, as in fig. 4, the passage of an electric current through a helix placed therein (the direction of the current in the upper half of the helix being that indicated by the arrow) will weaken

the force in the first and third quadrants, but will strengthen it in the second and fourth. With the aid of this simple fact we can solve every experiment made with the bismuth bars. For instance, it was found that when an observer stood before the magnet with a north pole to his right and a south pole to his left, a current passing through the upper half of the helix from the north to the south pole deflected a bar of ordinary bismuth, which had previously stood equatorial, so that the end presented to the observer moved towards the north pole. This deportment might be inferred from the constitution of the magnetic field; the bar places its ends in quadrants 1 and 3, that is, in the positions of weakest force.

The experiments with the other bar are capable of an explanation just as easy. Preserving the arrangement as in the last figure, the bismuth bar, which previously stood axial, would be deflected by the surrounding current,

FIG. 3.

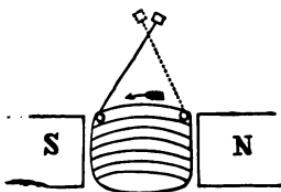
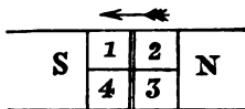


FIG. 4.



so that its two ends would occupy the quadrants 2 and 4, that is, the positions of strongest force. Now this is exactly what they did in the magnetic field before the passage of any current, for the bar set axial. It was first proved by Faraday, that the mass of a bismuth crystal was most strongly repelled when the repulsive force acted parallel to the planes of most eminent cleavage; and in the magnetic field the superior repulsion of these planes causes them always to take up that position where the force is a minimum. It is the equatorial setting of these planes which causes the bar at present under consideration to set axial. The planes of cleavage being thus the true indicators, we see that when these set from the first to the third quadrant, or in the line of weakest action, the ends of the bar must necessarily occupy the second and fourth, which is the deportment observed.

The little test-sphere can also be made available for examining the change brought about in the magnetic field by the introduction of a small bar of iron, as in the experiment of Plücker quoted by Faraday.¹ Removing the helix from the magnetic field, the little sphere was at liberty to traverse it from wall to wall. When the magnet was excited, the sphere passed slowly on to the pole to which it was nearest and came to rest against it. When forcibly brought into the centre of the magnetic field, after a moment's apparent hesitation it passed to one pole or the other with a certain speed; but when a bar of iron was brought underneath while it was central, this speed was considerably increased. Over the centre of the bar there was a position of unstable equilibrium for the sphere, from which it passed right or left, as the case might be, with greatly increased velocity. The distribution of the force appears in this case to have undergone a change represented by the line

¹ Phil. Mag., S. 3, vol. xxxvii. p. 104.

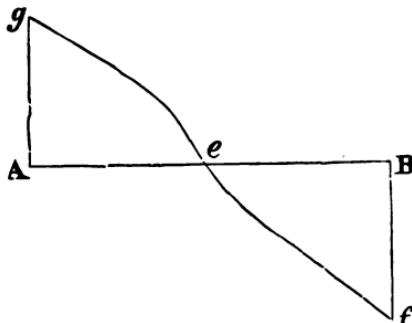
gef in the diagram. From the centre towards the poles the magnetic tension steepens suddenly, the quicker recession of a bismuth bar towards the equator, as observed by Plücker, being the consequence.

Assuming the law of action for a small magnetic sphere to be that it proceeds from weaker to stronger

places of force, we find that the passage of an electric current in the manner described so modifies the 'field' [between flat poles], that the positions of its two diagonals are of unequal values as regards the distribution of the force, the position of the field intersected by the diagonal which bisects 1 and 3, fig. 4, being weaker than the portion intersected by the diagonal which bisects 2 and 4.

But here the believer in diamagnetic polarity may enter his protest against the use which we have made of the assumption. 'I grant you,' he may urge, 'that in a simple magnetic field, consisting of the space before and around a single pole, what you assume is correct, that a magnetic sphere will pass from weaker to stronger places of action; but for a field into which several distinct poles throw their forces, the law by no means sufficiently expresses the state of things. If we place together two poles of equal strengths, but of opposite qualities, close to a mass of iron, it is an experimental fact that there is almost no attraction; and if they operate upon a mass of bismuth, there is no repulsion. Why? Do the magnetic rays, to express the thing popularly, annul each other by a species of interference before they reach the body; or

FIG 5.



does the one pole induce in the body the condition upon which the second pole acts in a sense contrary to the first, the two poles thus exactly neutralising each other? If the former, then I grant you that the magnetic field is rendered weaker, nay deprived of all force if you will, by the introduction of the second pole; but if the latter, then we must regard the field as possessing two systems of forces; and it is to the peculiar inductive property of the body, in virtue of which one system neutralises the other, that we must attribute the absence of attraction or repulsion. Once grant this, however, and the question of diamagnetic polarity, so far as you are concerned, is settled in the affirmative.'

Our hypothetical 'believer' mentions it as 'an experimental fact,' that if dissimilar poles of equal strengths operate upon a mass of bismuth there is no repulsion. This is Reich's result—a result which I have carefully tested and corroborated. I will now proceed to show the grounds which the believer in diamagnetic polarity might urge in support of his last assertion. A twelve-pound copper helix was removed from the limb of an electro-magnet and set upright. A magnetised sewing-needle being suspended from one end, the other end was caused to dip into the hollow of the spiral, and to rest against its interior surface. When a current was sent through the helix in a certain direction, the needle was repelled towards the axis of the coil; the same end of the needle, when suspended at half an inch distance from the *exterior* surface of the coil, was drawn strongly up against it. When the current was reversed, the end of the needle was attracted to the interior surface of the coil, but repelled from its exterior surface. If we suppose a little mannikin swimming along in the direction of the current, with his face towards the axis of the helix, the exterior surface of that end towards which his *left arm* would point

repels the north pole of a magnetic needle, while the interior surface of the same end *attracts* the north pole. The complementary phenomena were exhibited at the other end of the helix. Thus if we imagine two observers placed the one within and the other without the coil, the same end thereof would be a north pole to the one and a south pole to the other.

If we apply these facts to the case of the helix within the magnetic field, we see that each pole of the magnet had two contrary poles of the helix in contact with it; and we moreover find that the quadrants which we have denominated the strongest are those in which the poles of magnet and helix were in conjunction; while the quadrants which we have called weakest are those in which the poles of magnet and helix were in opposition.

'Which will you choose?' demands our hypothetical friend; 'either you must refer the weakening of a quadrant to magnetic interference, or you must conclude, that that induced state, whatever it be, which causes the bismuth to be repelled by the magnet, causes it to be *attracted* by the coil, the resultant being the difference of both forces. In the same manner the strengthening of a quadrant is accounted for by the fact, that here the induced state which causes the bismuth to be repelled by the magnet causes it to be repelled by the coil also, the resultant being the sum of both forces. The matter may be stated still more distinctly by reference to Reich's experiments.¹ Bringing a bundle of magnet-bars to bear upon a diamagnetic ball suspended to the end of a torsion-balance, he found that when similar poles were presented to the body, there was a very distinct repulsion; but that if one half of the poles were north and the other half south, there was no repulsion. Let us imagine the respective halves to be brought to bear upon the

¹ Phil. Mag., S. 3. vol. xxxiv. p. 127.

ball consecutively; the first half will cause it to recede to a certain distance; if the second and unlike half be now brought near, the ball will approach again, and take up its original position. The question therefore appears to concentrate itself into the following:—Is this “approach” due to the fact that the magnetic forces of the two halves annul each other before they reach the ball, or is it the result of a compensation of inductions in the diamagnetic body itself? If a sphere of soft iron be suspended from a thread, the north pole of a magnet will draw it from the plumb-line; if the south pole of an exactly equal magnet be brought close to the said north pole, the sphere will recede to the plumb-line. Is this recession due to a compensation of inductions in the sphere itself, or is it not? If the former, then, by all parity of reasoning, we must assume a similar compensation on the part of the bismuth.’

That bismuth, and diamagnetic bodies generally, suffer induction, will, I think, appear evident from the following considerations. The power of a magnet is practically ascertained by the mechanical effect which it is able to produce upon a body possessing a constant amount of magnetism,—a hard steel needle, for instance. The action of a magnet in pulling such a needle from the magnetic meridian may be expressed by a weight which acts at the end of a lever of a certain length. By easy practical rules we can ascertain when the pull of one magnet is twice or half the pull of another, and in such a case we should say that the former possesses twice or half the strength of the latter. If, however, these two magnets, with their powers thus fixed, be brought to bear upon a sphere of soft iron, the attraction of the one will be four times or a quarter that of the other. The strengths of the magnets being, however, in the ratio of 1 : 2, this attraction of 1 : 4 can only be explained by taking into account

the part played by the iron sphere. We are compelled to regard the sphere as an induced magnet, whose power is directly proportional to the inducing one. Were the magnetism of the sphere a constant quantity, a magnet of double power could only produce a double attraction; but the fact of the magnetism of the sphere varying directly as the source of induction leads us inevitably to the law of squares; and conversely, the law of squares leads us to the conclusion that the sphere has been induced.

These sound like truisms; but if they be granted, there is no escape from the conclusion that diamagnetic bodies are induced; for it has been proved by M. E. Becquerel and myself, that the repulsion of diamagnetic bodies follows precisely the same law as the attraction of magnetic bodies; the law of squares being true for both. Now were the repulsion of bismuth the result of a force applied to the mass alone, without induction, then, with a constant mass, the repulsion must be necessarily proportional to the strength of the magnet. But it is proportional to the square of the strength, and hence must be the product of induction.

In order to present magnetic phenomena intelligibly to the mind, a material imagery has been resorted to by philosophers. Thus we have the 'magnetic fluids' of Poisson and the 'lines of force' of Faraday. For the former of these Sir W. Thomson has recently substituted an 'imaginary magnetic matter.' The distribution of this 'matter' in a mass of soft iron, when operated on by a magnet, has attraction for its result. We have the same necessity for an image in the case of bismuth. If we imagine the two magnetic matters which are distributed by induction on a piece of iron to change places, we have a distribution which will cause the phenomena of bismuth. Hence it is unnecessary to assume the existence of any *new* matter in the case of

diamagnetic bodies, their deportment being accounted for by reference to a peculiarity of distribution. Further, the experiments of Reich, which prove that the matter evoked by one pole will *not* be repelled by an unlike pole, compel us to assume the existence of *two kinds* of matter, and this, if I understand the term aright, is polarity.

Note added, 1870.—The foregoing slight paper could have very little influence on the decision of so weighty a question. In the autumn of 1854 I therefore resumed the investigation with a desire to exhaust, if possible, the experimental portion of it. The following memoir contains an account of the inquiry. I had previously been examining the influence of organic structure upon the display of magnetism ; and had also been engaged with certain laws deduced by Plücker from his experiments as to the diminution of magnetism and diamagnetism with the distance. The account of these experiments precedes the real inquiry into the relations of magnetism to diamagnetism, and ought, perhaps, to have been published by itself.

FOURTH MEMOIR.

*ON THE NATURE OF THE FORCE BY WHICH
BODIES ARE REPELLED FROM THE POLES
OF A MAGNET.¹*

Introduction.

FROM the published account of his researches it is to be inferred, that the same heavy glass, by means of which he first produced the rotation of the plane of polarisation of a luminous ray, also led Faraday to the discovery of the diamagnetic force. A square prism of the glass, 2 inches long, and 0·5 of an inch thick, was suspended with its length horizontal between the two poles of a powerful electro-magnet : on developing the magnetism the prism moved round its axis of suspension, and finally set its length at right angles to a straight line drawn from the centre of one pole to that of the other. A prism of ordinary magnetic matter, similarly suspended, would, as is well known, set its longest dimension from pole to pole. To distinguish the two positions here referred to, Faraday introduced two new terms, which have since come into general use: he called the direction parallel to the line joining the poles, the *axial* direction, and that perpendicular to the said line, the *equatorial* direction.

The difference between this new action and ordinary magnetic action was further manifested when a fragment of the heavy glass was suspended before a single

¹ Phil. Trans. 1855, p. 1: being the Bakerian Lecture.

electro-magnetic pole : the fragment was repelled when the magnetism was excited. To the force which produced this repulsion Faraday gave the name of *diamagnetism*.

Numerous other substances were soon added to the heavy glass, and, among the metals, it was found that bismuth possessed the new property in a comparatively exalted degree. A fragment of this substance was forcibly repelled by either of the poles of a magnet ; while a thin bar of the substance, or a glass tube containing the bismuth in fragments, or in powder, suspended between the two poles of a horseshoe magnet, behaved exactly like the heavy glass, and set its longest dimension equatorial.

These exhaustive researches, which rendered manifest to the scientific world the existence of a pervading natural force, glimpses of which merely had been previously obtained by Brugmans and others, were made public at the end of 1845 ; and in 1847 Plücker announced his beautiful discovery of the action of a magnet upon crystallised bodies. His first result was, that when any crystal whatever was suspended between the poles of a magnet, with its optic axis horizontal, a repulsive force was exerted on the axis, in consequence of which it receded from the poles and finally set itself at right angles to the line joining them. Subsequent experiments, however, led to the conclusion, that the axes of optically negative crystals, only, experienced this repulsion, while the axes of positive crystals were attracted ; or, in other words, set themselves from pole to pole. The attraction and repulsion, here referred to, were ascribed by Plücker to the action of a force, independent of the magnetism or diamagnetism of the mass of the crystal.¹

¹ ‘The force which produces this repulsion is independent of the magnetic or diamagnetic condition of the mass of the crystal ; it diminishes less, as the distance from the poles of the magnet increases, than the magnetic and diamagnetic forces emanating from these poles and acting upon the crystal.’

Shortly after the publication of Plücker's first memoir, Faraday observed the remarkable magnetic properties of crystallised bismuth; and his researches upon this, and other kindred points, formed the subject of the Bakerian Lecture before the Royal Society for the year 1849.

Through the admirable lectures of Professor Bunsen on Electro-chemistry in 1848, I was first made acquainted with the existence of the diamagnetic force; and in the month of November 1849 my friend Professor Knoblauch, then of Marburg, now of the University of Halle, suggested to me the idea of repeating the experiments of Plücker and Faraday. He had procured the necessary apparatus with the view of prosecuting the subject himself, but the pressure of other duties prevented him from carrying out his intention. I adopted the suggestion and entered upon the inquiry in M. Knoblauch's cabinet. Our frequent conversations upon the subject led naturally to our making it a joint investigation. We published our

—Prof. Plücker in Poggendorff's *Annalen*, vol. lvii. No. 10; Taylor's Scientific Memoirs, vol. v. p. 353.

The forces emanating from the poles of a magnet are thus summed up by Plücker:—

1st. The magnetic force in a strict sense.

2nd. The diamagnetic action discovered by Faraday.

3rd. The action exerted on the optic axes of crystals (and that producing the rotation of the plane of polarisation which probably corresponds to it). *The second diminishes more with the distance than the first, and the first more than the third.*—Taylor's Scientific Memoirs, vol. v. p. 380.

The crystal (cyanite) does not point according to the magnetism of its substance, *but only in obedience to the magnetic action upon its optic axes.*—Letter to Faraday, Phil. Mag. vol. xxxiv. p. 451. The italics in all cases are Plücker's own.

De la Rive states the view of Plücker to be:—‘that the axis in its quality as axis, and independently of the very nature of the substance of the crystal, enjoys peculiar properties, more frequently in opposition to those possessed by the substance itself, or which at least are altogether independent of it.’—Treatise on Electricity, vol. i. p. 359.

results in two papers, the first of which, containing a brief account of some of the earliest experiments, appeared in the 'Philosophical Magazine' for March 1850, and some time afterwards in Poggendorff's *Annalen*; while the second and principal memoir appeared in the 'Philosophical Magazine' for July 1850, and in Poggendorff's *Annalen* about January 1851.¹ I afterwards continued my researches in the private laboratory of Professor Magnus of Berlin, who, with prompt kindness and a lively interest in the furtherance of the inquiry, placed all necessary apparatus at my disposal. The results of this investigation are described in a paper published in the 'Philosophical Magazine' for September 1851, and in Poggendorff's *Annalen*, vol. lxxxiii.

In these memoirs it was shown that the law according to which the axes of positive crystals are attracted and those of negative crystals repelled, was contradicted by the deportment of numerous crystals both positive and negative. It was also proved that the force which determined the position of the optic axes in the magnetic field was not independent of the magnetism or diamagnetism of the mass of the crystal; inasmuch as two crystals, of the same form and structure, exhibited altogether different effects, when one of them was magnetic and the other diamagnetic. It was shown, for example, that pure carbonate of lime was diamagnetic, and always set its optic axis equatorial; but that when a portion of the calcium was replaced by an isomorphous magnetic constituent, which neither altered the structure nor affected the perfect transparency of the crystal, the optic axis set itself from pole to pole. The various complex phenomena exhibited

¹ The memoirs in the 'Philosophical Magazine' were written by myself, and the second one has, I believe, been translated into German by Dr. Krönig; the papers in Poggendorff's *Annalen* were edited by Knoblauch.—J. T.

by crystals in the magnetic field were finally referred to the modification of the magnetic and diamagnetic forces by the peculiarities of molecular arrangement.

This result is in perfect conformity with all that we know experimentally regarding the connection of matter and force. Indeed it may be safely asserted that every force which makes matter its vehicle of transmission must be influenced by the manner in which the material particles are grouped together. The phenomena of double refraction and polarisation illustrate the influence of molecular aggregation upon light. Wertheim has shown that the velocity of sound through wood, *along* the fibre, is about five times its velocity *across* the fibre : De la Rive, de Candolle, and myself have shown the influence of the same molecular grouping upon the propagation of heat. In the first section of the present memoir, the influence of the molecular structure of wood upon its magnetic deportment is described : De Senarmont has shown that the structure of crystals endows them with different powers of calorific conduction in different directions : Knoblauch has proved the same to be true, with regard to the transmission of radiant heat : Wiedemann finds the passage of frictional electricity along crystals to be affected by structure ; and some experiments, which I have not yet had time to follow out, seem to prove, that bismuth may, by the approximation of its particles, be caused to exhibit, in a greatly increased degree, those singular effects of induction which are so strikingly exhibited by copper, and other metals of high conducting power.

Indeed the mere *à priori* consideration of the subject must render all the effects here referred to extremely probable. Supposing the propagation of the forces to depend upon a subtle agent, distinct from matter, it is evident that the progress of such an agent from particle to

particle must be influenced by the manner in which these particles are arranged. If the particles be twice as near each other in one direction as in another, it is certain that the agent spoken of will not pass with the same facility in both directions. Or supposing the effects to which we have alluded to be produced by motion of some kind, it is just as certain that the propagation of this motion must be affected by the manner in which the particles which transmit it are grouped together. Whether, therefore, we take the old hypothesis of imponderables or the new, and more philosophic one, of modes of motion, the result is still the same.

If this reasoning be correct, it would follow that, if the molecular arrangement of a body be changed, such a change will manifest itself by an alteration of deportment towards any force operating upon the body: the action of compressed glass upon light, which Wertheim in his recent researches¹ has so beautifully turned to account in the estimation of pressures, is an illustration in point; and the inference also receives the fullest corroboration from experiments, some of which are recorded in the papers already alluded to, and which show that all the phenomena of magne-crystallic action may be produced by simple mechanical agency. What the crystalline forces do in the one case, mechanical force, under the control of the human will, accomplishes in the other. A crystal of carbonate of iron, for example, suspended in the magnetic field, exhibits a certain deportment: the crystal may be removed, pounded into the finest dust, and the particles so put together that the mass shall exhibit the same deportment as before. A bismuth crystal suspended in the magnetic field, with its planes of principal cleavage vertical, will set those planes equatorial; but when the crystalline planes are squeezed sufficiently together by a suitable

¹ Phil. Mag. October and November, 1854.

mechanical force, this deportment is quite changed, the line which formerly set equatorial now setting axial.¹

Thus we find that the influence of crystallisation may be perfectly imitated, and even overcome, by simple mechanical agencies. It would of course be perfectly unintelligible were we to speak of any direct action of the magnetic force upon the force by which the powdered carbonate of iron, or the solid cube of bismuth, is compressed; such an idea, however, appears scarcely less tenable than the notion entertained by distinguished men who have worked at this subject; namely, that there is a direct action of the magnet upon the molecular forces which built the crystal. The function of such forces, as regards the production of the effects, is, I believe, *mediate*; the molecular forces are exerted in placing the particles in position, and the subsequent phenomena, whether exhibited in magne-crystalline action, in the bifurcation and polarisation of a luminous ray, or in the modification of any other force transmitted through the crystal, are not due to the action of force upon force, except through the intermediation of the particles referred to.²

The foregoing introductory statement will, perhaps, sufficiently indicate the present aspect of this question. The object I proposed to myself in commencing the inquiry now laid before the Royal Society was to obtain, if possible, clearer notions of the nature of the diamagnetic

¹ Phil. Mag. vol. ii. Ser 4. p. 183.

² The influence of the molecular aggregation probably manifests itself on a grand scale in nature. The Snowdon range of mountains, for example, is principally composed of slate rock, whose line of strike is nearly north and south. The magnetic properties of this rock I find, by some preliminary experiments, to be very different along the cleavage from what they are across it. I cannot help thinking that these vast masses, in their present position, must exert a different action on the magnetic needle from that which would be exerted if the line of strike were east and west.

force than those now prevalent ; for though, in the preceding paragraphs, we have touched upon some of the most complex phenomena of magnetism and diamagnetism, and are able to reproduce these phenomena at will, the greatest diversity of opinion still prevails as to the real relationship of the two forces. The magnetic force, we know, embraces both attraction and repulsion, thus exhibiting that wonderful dual action which we are accustomed to denote by the term polarity. Faraday was the first who proposed the hypothesis that diamagnetic bodies, operated on by magnetic forces, possess a polarity 'the same in kind as, but the reverse in direction of, that acquired by iron, nickel, and ordinary magnetic bodies under the same circumstances.'¹ W. Weber sought to confirm this hypothesis by a series of experiments, wherein the excitement of the supposed diamagnetic polarity was applied to the generation of induced currents—apparently with perfect success. Faraday afterwards showed, and his results were confirmed by Verdet, that effects similar to those described by the distinguished German were to be attributed, not to the excitement of diamagnetic polarity, but to the generation of ordinary induced currents in the metallic mass. On the question of polarity Faraday's results were negative, and he therefore, with philosophic caution, holds himself unpledged to his early opinion. Weber, however, still retains his belief in the reverse polarity of diamagnetic bodies, whereas Weber's countryman von Feilitzsch, in a series of memoirs recently published in Poggendorff's *Annalen*, contends that the polarity of diamagnetic bodies is precisely the same as that of magnetic ones. In this unsettled state of the question nothing remained for me but to undertake a complete examination of the nature of the diamagnetic force, and a thorough comparison of its

¹ Experimental Researches, 2429, 2430.

phenomena with those of ordinary magnetism. This has been attempted in the following pages : with what success it must be left to the reader to decide.

Before entering upon the principal inquiry, I will introduce one or two points which arose incidentally from the investigation, and which appear to be worth recording.

ON THE MAGNETIC PROPERTIES OF WOOD.

No experiments have yet been made to determine the influence of structure upon the magnetic deportment of this substance ; and even on the question whether it is magnetic, like iron, or diamagnetic, like bismuth, differences of opinion appear to prevail. Such differences are to be referred to the extreme feebleness of the force proper to the wood itself, and its consequent liability to be masked by extraneous impurity. In handling the substance intended for experiment the fingers must be kept perfectly clean, and frequent washing is absolutely necessary. After reducing the substance to a regular shape, so as to annul the influence of exterior form, its outer surface must be carefully removed by glass, and the body afterwards suspended by a very fine fibre between the poles of a strong electro-magnet.

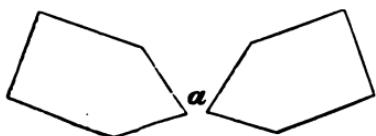
The first step in the present inquiry was to ascertain whether the substance examined was paramagnetic¹ or diamagnetic. It is well known, that, in experiments of this kind, movable masses, or poles, of soft iron are placed upon the ends of the electro-magnet, the distance between the poles being varied to suit the experiment. A cube of wood

¹ The effects exhibited by iron and by bismuth come properly under the general designation of *magnetic* phenomena : to render their subdivision more distinct Mr. Faraday has recently introduced the word *paramagnetic* to denote the old magnetic effects, of which the action of iron is an example. Wherever the word *magnetic* occurs, without the prefix, it is always the old action that is referred to.

being suspended in front of a pointed pole of this kind, if, on exciting the magnet, the cube was repelled by the point, it was regarded as diamagnetic; if attracted, it

was considered to be paramagnetic. The force is considerably intensified by placing the two movable poles as in fig. 1, and suspending the cube at α on the same level with the points; a diamagnetic body

FIG. 1.



placed there is, on the development of the magnetic force, forcibly driven *from* the line which unites the points, while a magnetic body is forcibly drawn in between them.

Having thus observed the deportment of the mass, the cube was next suspended between the *flat* ends of the poles sketched in fig. 1. The parallel faces were about three-quarters of an inch apart, and in each case the fibre of the suspended wood was horizontal. The specimen first examined was Beef-wood: suspended in the position α , fig. 1, the mass was repelled: suspended between the flat poles, on exciting the magnet, the cube, if in an oblique position, turned and set its fibre equatorial. By suitably breaking and closing the circuit the cube could be turned 180° round and held in this new position. The axial position of the ligneous fibre was one of unstable equilibrium, from which, if it diverged in the slightest degree right or left, the cube turned and finally set its fibre equatorial. The following is a statement of the results obtained with thirty-five different kinds of wood:—

Table I.

Name of wood	Deportment of mass	Deportment of structure	Remarks
1. Beef-wood . .	Diamagnetic	Fibre equatorial	
2. Black ebony . .	"	"	
3. Box-wood . .	"	"	
4. Second specimen . .	"	"	
5. Brazil-wood . .	"	"	
6. Braziletto . .	"	"	Action decided
7. Bullet-wood . .	"	"	Action decided
8. Cam-wood . .	"	"	
9. Cocoa-wood . .	"	"	
10. Coromandel-wood . .	"	"	
11. Green Ebony . .	"	"	Action strong
12. Green-heart . .	"	"	Action strong
13. Iron-wood . .	"	"	Action strong
14. King-wood . .	"	"	Action strong
15. Locust-wood . .	"	"	
16. Maple . .	"	"	Action decided
17. Lance-wood . .	"	"	Action decided
18. Olive-tree . .	"	"	
19. Peruvian-wood.	"	"	Action strong
20. Prince's-wood . .	"	"	
21. Camphor-wood.	"	"	
22. Sandal-wood . .	"	"	
23. Satin-wood . .	"	"	
24. Tulip-wood . .	"	"	
25. Zebra-wood . .	"	"	
26. Botany Bay Oak . .	"	"	
27. Mazatlan-wood.	"	"	Action strong
28. Tamarind-wood . .	"	"	Action decided
29. Sycamore . .	"	"	Action decided
30. Beech . .	"	"	Action decided
31. Ruby-wood . .	"	"	
32. Jacca . .	"	"	
33. Oak . .	"	"	Action strong
34. Yew . .	"	"	Action feeble
35. Black Oak . .	Paramagnetic	"	Action decided

The term 'decided' is here used to express an action more energetic than ordinary, but in no case does the result lack the decision necessary to place it beyond doubt. It must also be remarked that the term 'strong' is used in relation to the general deportment of wood ; for, compared

with the action of many other diamagnetic bodies, the strongest action of wood is but feeble. Simple as the problem may appear, it required considerable time and care to obtain the results here recorded. During the first examination of the cubes eight anomalies presented themselves—in eight cases the fibre set either oblique or axial. The whole thirty-five specimens were carefully rescraped with glass and tested once more; still two remained, which, though repelled as masses, persistently set with the fibre axial, and oscillated round this position so steadily as to lead to the supposition that the real deportment of the substance was thus exhibited. I scraped these cubes ten times successively, and washed them with all care, but the deportment remained unchanged. The cubes, for the sake of reference, had been stamped with diminutive numbers by the maker of them; and I noticed at length, that in these two cases a trace of the figures remained; on removing, from each, the whole surface which bore the stamp, the cubes forsook the axial position, and set, like the others, with the fibre equatorial.

The influence of the mere *form* of an impurity was here very prettily exhibited. The cubes in question had been stamped (probably by a steel tool) with the numbers 33 and 37, which lay in the line of the fibre; the figures, being dumpy little ones, caused an elongation of the magnetic impurity along the said line, and the natural consequence of this elongation was the deportment above described.

Of the thirty-five specimens examined one proved to be paramagnetic. Now, it may be asked, if the views of molecular action stated in the foregoing pages be correct, how is it that this paramagnetic cube sets its fibre equatorial? The case is instructive. The substance (bog-oak) had been evidently steeped in a liquid containing a small quantity of iron in solution, whence it derived its mag-

netism ; but here we have no substitution of paramagnetic molecules for diamagnetic ones, as in the cases referred to. The extraneous magnetic constituent is practically indifferent as to the direction of magnetisation, and it therefore accommodates itself to the directive action of the wood to which it is attached.

ON THE ROTATION OF BODIES BETWEEN POINTED MAGNETIC POLES.

In his experiments on charcoal, wood-bark, and other substances, Plücker discovered some very curious phenomena of rotation, which occurred on removing the substance experimented on from one portion of the magnetic field to another. To account for these phenomena, he assumed, that in the substances which exhibited the rotation, two antagonistic forces were perpetually active—a repulsive force which caused the substance to assume one position ; and an attractive force which caused it to assume a different position : that, of these two forces, the repulsive diminished more quickly than the attractive, when the distance of the body from the poles was augmented. Thus, the former, which was predominant close to the poles, succumbed to the latter when a suitable distance was attained —hence arose the observed rotation.

Towards the conclusion of the memoir published in the September number of the ‘Philosophical Magazine’ for 1851, I stated that it was my intention further to examine this highly ingenious theory. I shall now endeavour to fulfil the promise then made, and to state, as briefly as I can, the real law which regulates these complex phenomena.

The masses of soft iron sketched in fig. 1 were placed upon the ends of the electro-magnet, with their points facing each other ; between the points the body to be examined was suspended by a fine fibre, and could be raised or lowered by turning a milled head. The body was

first suspended at the level of the points and its deportment noted, it was then slowly elevated, and the change of position, if any, was observed. It was finally permitted to sink below the points and its deportment there noted also.

The following is a statement of the results; the words 'equatorial' (E) and 'axial' (A) imply that the longest horizontal dimension of the substance examined took up the position denoted by each of these words respectively. The manner in which the bars were prepared is explained further on.

Table II.

Name of substance	Horizontal dimensions	Deportment of mass	Position		
			Between poles	Above	Below
1. Tartaric acid . .	0·5 × 0·1	Diamagnetic	E	A	A
2. A second specimen.	0·4 × 0·1	"	E	A	A
3. Red ferrocyanide of potassium . .	0·6 × 0·1	Paramagnetic	A	E	E
4. A second prism. . .	0·9 × 0·12	"	A	E	E
5. Citric acid . . .	0·55 × 0·25	Diamagnetic	E	A	A
6. A second specimen.	0·48 × 0·2	"	E	A	A
7. Beryl	0·45 × 0·1	Paramagnetic	A	E	E
8. Saltpetre . . .	0·6 × 0·3	Diamagnetic	E	A	A
9. Nitrate of soda . .	0·6 × 0·12	"	E	A	A
10. Sulphate of iron .	0·7 × 0·15	Paramagnetic	A	E	E
11. A second specimen.	0·6 × 0·08	"	A	E	E
12. A third specimen .	1·0 × 0·18	"	A	E	E
13. Calcareous spar . .	0·5 × 0·1	Diamagnetic	E	A	A
14. A full crystal . .	—	"	E	A	A
15. Carbonate of iron.	0·5 × 0·1	Paramagnetic	A	E	E
16. Carbonate of iron powdered and compressed . . .	0·9 × 0·18	"	A	E	E
17. Compressed disc .	0·8 × 0·08	"	A	E	E
18. Bismuth	0·95 × 0·15	"	E	A	A
19. The same com- pressed	0·7 × 0·05	"	E	A	A
20. The same powdered and compressed . .	0·6 × 0·07	Diamagnetic	E	A	A
21. Cylinder of the same. . . .	1·0 × 0·15	"	E	A	A
22. Tourmaline . . .	2·1 × 0·1	Paramagnetic	A	E	E
23. A second specimen.	1·1 × 0·1	"	A	E	E
24. A third	0·9 × 0·1	"	A	E	E

Table II.—continued.

Name of substance	Horizontal dimensions	Deportment of mass	Position		
			Between poles	Above	Below
25. Sulphate of nickel.	0·9 × 0·3	Paramagnetic	A	E	E
26. A second specimen.	0·6 × 0·2	"	A	E	E
27. Heavy spar . . .	0·38 × 0·18	Diamagnetic	E	A	A
28. A second specimen.	0·4 × 0·18	"	E	A	A
29. Carbonate of tin powdered and compressed . . .	0·34 × 0·04 length 6 times width	"	E	A	A
30. A second specimen.	"	"	E	A	A
31. Ammonio - phosphate of magnesia powdered and compressed . . .	0·3 × 0·06	"	E	A	A
32. A second specimen.	0·5 × 0·07	"	E	A	A
33. Carbonate of magnesia powdered and compressed .	0·45 × 0·04	"	E	A	A
34. Sulphate of magnesia. . . .	0·32 × 0·2	"	E	A	A
35. A second specimen.	0·25 × 0·15	"	E	A	A
36. Flour compressed .	0·24 × 0·04	"	E	A	A
37. Oxalate of cobalt .	0·6 × 0·08	Paramagnetic	A	E	E

These experiments might be extended indefinitely, but we have sufficient here to enable us to deduce the law of action. In the first place we notice, that all those substances which set equatorial between the points and axial above and below them, are *diamagnetic*; while all those which set axial between the points and equatorial above and below them, are *paramagnetic*. When any one of the substances here named is reduced to the spherical form, this rotation is not observed. I possess, for example, four spheres of calcareous spar, and when any one of them is suspended between the points, it takes up a position which is not changed when the sphere is raised or lowered; the crystallographic axis sets equatorial in all positions. A sphere of compressed carbonate of iron, suspended between the points, also sets that diameter along which the pressure is exerted from pole to pole, and continues to

do so when raised or lowered. A sphere of compressed bismuth, on the other hand, sets its line of compression always equatorial. The position taken up by the *spheres* depends solely upon the *molecular structure* of the substances which compose them; but, when the mass is *elongated*, another action comes into play. Such a mass being suspended with its length horizontal, the *repulsion of its ends* constitutes a mechanical couple which increases in power with the length of the mass; and when the body is long enough, and the local repulsion of the ends strong enough, the couple, when it acts in opposition to the directive tendency due to structure, is able to overcome the latter and to determine the position of the mass.

In all the cases cited, it was so arranged that the length of the body and its structure should act in opposition to each other. Tartaric acid and citric acid cleave with facility in one direction, and, in the specimens used, the planes of cleavage were perpendicular to the length of the body. In virtue of the structure, these planes tended to set equatorial, but the repulsion of the elongated mass by the points prevented this, and caused the planes to set axial. When, however, the body was raised or lowered out of the region of local repulsion, and into a position where the distribution of the force was more uniform, the advantage due to length became so far diminished that it was overcome, in turn, by the influence of structure, and the planes of cleavage turned into the equatorial position. In the specimen of saltpetre the shortest horizontal dimension was parallel to the axis of the crystal, which axis, when the influence of form is destroyed, always sets equatorial. A full crystal of calcareous spar will, when the magnetic distribution is tolerably uniform, always set its axis at right angles to the line joining the poles; but the axis is the shortest dimension of the crystal, and, between the points, this mechanical disadvantage compels

the influence of structure to succumb to the influence of shape. A cube of calcareous spar, in my possession, may be caused to set the optic axis from pole to pole between the points, but this is evidently due to the elongation of the mass along the diagonals; for, when the corner of the cube succeeds in passing the point of the pole, the mass turns its axis with surprising energy into the equatorial position, round which it oscillates with great vivacity. Counting the oscillations, I found that eighty-two were performed by the cube, when its axis was equatorial, in the time required to perform fifty-nine, when the axis stood from pole to pole. Heavy spar and coelestine are beautiful examples of directive action. These crystals, as is well known, can be cloven into prisms with rhombic bases: the principal cleavage is parallel to the base of the prism, while the two subordinate cleavages constitute the sides. If a short prism be suspended in a tolerably uniform field of force, so that its rhombic ends shall be horizontal, on exciting the magnet the short diagonal will set equatorial, as shown in fig. 2. If the prism be suspended with its axis and the short diagonal horizontal, the long diagonal being therefore vertical, the short diagonal will retain the equatorial position, while the axis of the prism sets axial as in fig. 3. If the prism be suspended with its long diagonal and axis horizontal, the short diagonal being vertical, and its directive power therefore annulled, the axis will take up the equatorial position, as in fig. 4.

Now as the line which sets equatorial in diamagnetic bodies is that in which the magnetic repulsion acts most strongly,¹ the crystal before us furnishes a perfect example of a substance possessing three rectangular magnetic axes, no two of which are equal. In the experiment cited in Table II. page 124, the mass was so cut that the short

¹ Phil. Mag., S. 4. vol. ii. p. 177.

diagonal of the rhombic base was perpendicular to the length of the specimen. Carbonate of tin, and the other powders, were compressed by placing the powder between two clean plates of copper, and squeezing them together in

FIG. 2.

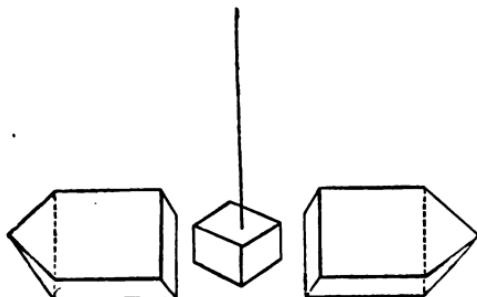


FIG. 3.

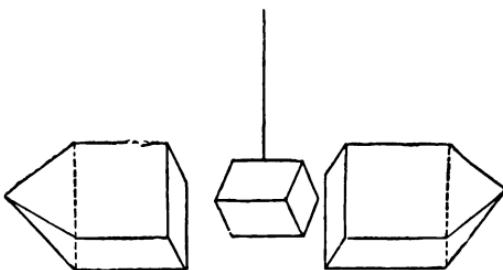
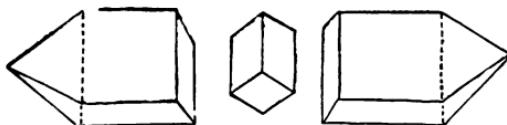


FIG. 4.



a strong vice. The line of compression in diamagnetic bodies, as already stated, always sets equatorial, when the field of force is uniform, or approximately so; but, between points, the repulsion of the ends furnishes a couple strong

enough to overcome this directive action, causing the longest dimension of the mass to set equatorial, and consequently its line of compression axial.

The antithesis between the deportment of diamagnetic bodies and of paramagnetic ones is thus far perfect. Between the points the former class set equatorial, the latter axial. Raised or lowered, the former set axial, the latter equatorial. The simple substitution of an attractive for a repulsive force produces this difference of effect. A sphere of ferrocyanide of potassium, for example, always sets the line perpendicular to the crystallographic axis from pole to pole; but when we take a full crystal, whose dimension along its axis, as in one of the cases before us, is six times the dimension at right angles to the axis, the attraction of the ends is sufficient to overcome the directive action due to structure, and to pull the crystal into the axial position between the points. In a field of uniform force, or between flat poles, the length sets equatorial, and it is, as already insisted on, the partial attainment of such a field, at a distance from the points, that causes the crystal to turn from axial to equatorial when it is raised or lowered. Beryl is a paramagnetic crystal, and when the influence of form is annulled, it always sets a line perpendicular to the axis of the crystal from pole to pole; a *cube* of this crystal, at present in my possession, shows this deportment whether the poles are pointed or flat: but in the specimen examined the dimension of the crystal along its axis was greatest, and hence the deportment described. It is needless to dwell upon each particular paramagnetic body: the same principle was observed in the preparation and choice of all of them; namely, that the line which, in virtue of the internal structure of the substance, would set axial, was transverse to the length of the body. The directive action due to structure was thus brought into opposition with the tendency of magnetic bodies to set their longest

dimension from pole to pole : between the points the latter tendency was triumphant ; at a distance, on the contrary, the influence of structure prevailed.

The substance which possesses this directive action in the highest degree is carbonate of iron : when a lozenge, cloven from the crystalline mass, is suspended from the angle at which the crystallographic axis issues, there is great difficulty in causing the plate to set axial. If the points are near, on exciting the magnetism the whole mass springs to one or the other of the points ; and when the points are distant, the plate, although its length may be twenty times its thickness, will set strongly equatorial. An excitation by one cell is sufficient to produce this result. In the experiment cited in the table the residual magnetism was found to answer best, as it permitted the ends of the plate to be brought so near to the points that the mass was pulled into the axial position. When the magnet was more strongly excited, and the plate raised so far above the points as to prevent its springing to either of them, it was most interesting to watch the struggle of the two opposing tendencies. Neither the axial nor the equatorial position could be retained ; the plate would wrench itself spasmodically from one position into the other, and, like a human spirit operated on by conflicting passions, find rest nowhere.

The conditions which determine the curious effects described in the present chapter may be briefly expressed as follows :—

An elongated diamagnetic body being suspended in the magnetic field, if the shortest horizontal dimension tend, in virtue of the internal structure of the substance, to set equatorial, it is opposed by the tendency of the longest dimension to take up the same position. Between the pointed poles the influence of length usually predominates ; above the points and below them the directive action due to structure prevails.

Hence, the rotation of a diamagnetic body, on being raised or lowered, is always from the equatorial to the axial position.

If the elongated mass be magnetic, and the shortest dimension of the mass tend, in virtue of its structure, to set from pole to pole, it is opposed by the tendency of the longest dimension to take up the same position. Between the points the influence of length is paramount; above and below the points the influence of structure prevails.

Hence, the rotation of magnetic bodies, on being raised or lowered, is always from the axial to the equatorial position.

The error of the explanation which referred many of the above actions to the presence of two conflicting forces, one of which diminished with the distance in a quicker ratio than the other, lies in the supposition, that the assuming of the axial position proved a body to be magnetic, while the assuming of the equatorial position proved a body to be diamagnetic. This assumption was perfectly natural in the early stages of diamagnetic research, when the modification of magnetic force by structure was unknown. Experience however proves that the total mass of a magnetic body continues to be attracted after it has assumed the equatorial position, while the total mass of a diamagnetic body continues to be repelled after it has taken up the axial one.

ON THE DISTRIBUTION OF THE MAGNETIC FORCE BETWEEN TWO FLAT POLES.

In experiments where a uniform distribution of the magnetic force is desirable, flat poles, or magnetised surfaces, have been recommended. It has long been known that the force proceeds with great energy from the edges of such poles: the increase of force from the centre to the edge has been made the subject of a special

investigation by Von Kolke.¹ The central portion of the magnetic field, or space between two such magnetised surfaces, has hitherto been regarded as almost perfectly uniform, and indeed for all ordinary experiments the uniformity is sufficient. But, when we examine the field carefully, we find that the uniformity is not perfect. Substituting, for the sake of convenience, the edge of a pole for a point, I studied the phenomena of rotation described in the last section, in a great number of instances, by comparing the deportment of an elongated body, suspended in the centre of the space between two flat poles, with its deportment when suspended between the top or the bottom edges. Having found that the fibre of wood, in masses where form had no influence, always set equatorial, I proposed to set this tendency to contend with an elongation of the mass in a direction at right angles to the fibre. For this purpose, thirty-one little wooden bars were carefully prepared and examined, the length of each bar being about twice its width, and the fibre coinciding with the latter dimension. The bars were suspended from an extremely fine fibre of cocoon silk, and in the centre of the magnetic field each one of them set its length axial, and consequently its fibre equatorial. Between the top and bottom edges, on the contrary, each piece set its longest dimension equatorial, and consequently the fibre axial.

For some time I referred the axial setting of the mass, in the centre of the field, to the directive action of the fibre, though, knowing the extreme feebleness of this directive action, I was surprised to find it able to accomplish what the experiments exhibited. The thought suggested itself, however, of suspending the bars with both the long dimension and the fibre vertical, in which position the latter could have no directive influence. Here also, to my sur-

¹ Poggendorff's *Annalen*, vol. lxxxi. p. 321.

prise, the directive action, though slightly weakened, was the same as before: in the centre of the field the bars took up the axial position. Bars of sulphur, wax, salt of hartshorn, and other diamagnetic substances were next examined: they all acted in the same manner as the wood, and thus showed that the cause of the rotation lay, not in the structure of the substances, but in the distribution of the magnetic force around them. This distribution in fact was such, that the straight line which connected the centre of one pole with that of the opposite one was the line of weakest force. Ohm represents the distribution of electricity upon the surfaces of conductors by regarding the tensions as ordinates, and erecting them from the points to which they correspond, the steepness of the curve formed by uniting the ends of the ordinates being the measure of the increase or diminution of tension. Taking the centre of the magnetic field as the origin, and drawing horizontal lines axial and equatorial, if we erect the magnetic tensions along these lines, we shall find a steeper curve in the equatorial than in the axial direction. This may be proved by suspending a bit of carbonate of iron in the centre of the magnetic field; on exciting the magnet, the suspended body will move, not to the nearest portion of the flat pole, though it may be not more than a quarter of an inch distant, but equatorially towards the edges, though they may be two inches distant. The little diamagnetic bars referred to were therefore pushed into the axial position by the force acting with superior power in an equatorial direction.

The results just described are simply due to the recession of the ends of an elongated body from places of stronger to those of weaker force; but it is extremely instructive to observe how this result is modified by structure. If, for example, a plate of bismuth be suspended between the poles with the plane of principal

cleavage vertical, the plate will assert the equatorial position from top to bottom; and in the centre with almost the same force as between the edges. The cause of this lies in the structure of the bismuth. Its position depends not so much upon the character of the magnetic field around it, as upon the direction of the force *through* it. I will not, however, anticipate matters by entering further upon this subject at present.

COMPARATIVE VIEW OF PARAMAGNETIC AND DIAMAGNETIC PHENOMENA.

1. *State of Diamagnetic Bodies under Magnetic Influence.*

When a piece of iron is brought near a magnet, it is attracted by the latter: this attraction is not the act of the magnet alone, but results from the mutual action of the magnet and the body upon which it operates. The iron in this case is said to be magnetised by influence; it becomes itself a magnet, and the intensity of its magnetisation varies with the strength of the influencing magnet. Poisson figured the act of magnetisation as consisting of the decomposition of a neutral magnetic fluid into north and south magnetism, the amount of the decomposition being proportional to the strength of the magnet which produces it. Ampère, discarding the notion of magnetic fluids, figured the molecules of iron as surrounded by currents of electricity, and conceived the act of magnetisation to consist in setting the planes of these molecular currents parallel to each other: the degree of parallelism, or in other words, the intensity of the magnetisation, depending, as in Poisson's hypothesis, upon the strength of the influencing magnet.

The state into which the iron is here supposed to be thrown is a state of constraint, and when the magnet is

removed, the substance returns to its normal condition. Poisson's separated fluids rush together once more, and Ampère's molecular currents return to their former irregular positions. As our knowledge increases, we shall probably find both hypotheses inadequate to represent the phenomena ; the only thing certain is, that the iron, when acted upon by the magnet, is thrown into an unusual condition, in virtue of which it is attracted ; and that the intensity of this condition is a function of the force which produces it.

There are, however, bodies which, unlike iron, offer a great resistance to the imposition of the magnetic state, but when once they are magnetised they do not, on the removal of the magnet, return to their neutral condition, but retain the magnetism impressed on them. It is in virtue of this quality that steel can be formed into compass needles and permanent magnets. This power of resistance and retention is named by Poisson coercive force.

Let us conceive a body already magnetised, and in which coercive force exists in a very high degree—a piece of very hard steel for example—to be brought near a magnet, the strength of which is not sufficient to magnetise the steel further. To simplify the matter, let us fix our attention upon the south pole of the magnet, and conceive it to act upon the north pole of the piece of steel. Let the magnetism of the said south pole, referred to any unit, be M , and of the north pole of the steel, M' ; then their mutual attraction, at the unit of distance, is expressed by the product MM' . Conceive now the magnet to increase in power from M to nM , the steel being still supposed hard enough to resist magnetisation by influence ; the mutual attraction now will be

$$nMM'$$

or n times the former attraction ; hence when a variable

magnetic pole acts on an opposite one of constant power, the attraction is proportional to the simple strength of the former.

Let us now take a body whose magnetisation varies with that of the magnet: a south pole of the strength M induces in such a body a north pole of the strength M' , and the attraction which results from their mutual action is

$$MM'.$$

Let the strength of the influencing south pole increase from M to nM ; then, assuming the magnetism of the body under influence to increase in the same ratio, the strength of the above-mentioned north pole will become nM' , and the attraction, expressed by the product of both, will be

$$n^2 MM' ;$$

that is to say, the attraction of a body magnetised by influence, and whose magnetism varies as the strength of the influencing magnet, is proportional to the *square of the strength* of the latter.

Here then is a mark of distinction between those bodies which have their power of exhibiting magnetic phenomena conferred upon them by the magnet, and those whose actions are dependent upon some constant property of the mass: in the latter case the resultant action will be simply proportional to the strength of the magnet, while in the former case a different law of action will be observed.¹

The examination of this point lies at the very foundation of our inquiries into the nature of the diamagnetic force. Is the repulsion of diamagnetic bodies dependent merely on the mass considered as ordinary matter, or is it

¹ This test was first pointed out in a paper on the Polarity of Bismuth, Phil. Mag. Nov. 1851, p. 333. I have reasons, however, to know that the same thought occurred to Poggendorff previous to the publication of my paper.—J. T.

due to some condition impressed upon the mass by the influencing magnet? This question admits of the most complete answer either by comparing the increase of repulsion with the increase of power in the magnet which produces the repulsion, or by comparing the attraction of a paramagnetic body, which we know to be thrown into an unusual condition, with the repulsion of a diamagnetic body, whose condition we would ascertain.

Bars of iron and bismuth, of the same dimensions, were submitted to the action of an electro-magnet, which was caused gradually to increase in power; commencing with an excitation by one cell, and proceeding up to an excitation by ten or fifteen. The strength of the current was in each case accurately measured by a tangent galvanometer. The bismuth bar was suspended between the two flat poles, and, when the magnet was excited, it took up the equatorial position. The iron bar, if placed directly between the poles, would, on the excitation of the magnetism, infallibly spring to one of them; hence it was removed to a distance of 2 feet 7 inches from the centre of the space between the poles, and in a direction at right angles to the line which united them. The magnet being excited, the bar, in each case, was drawn a little aside from its position of equilibrium and then liberated, a series of oscillations of very small amplitude followed, and the number of oscillations accomplished in a minute was carefully ascertained. Tables III. and IV. contain the results of experiments made in the manner described with bars of iron and bismuth of the same dimensions.

Table III.

Bar of iron, No. 1.—Length 0·8 of an inch; width 0·13 of an inch; depth 0·15 of an inch.

Strength of current	Attraction
168	168 ²
214	204 ²
248	253 ²
274	275 ²
323	313 ²
362	347 ²
385	374 ²
411	385 ²

Table IV.

Bar of Bismuth, No. 1.—Length 0·8 of an inch; width 0·13 of an inch; depth 0·15 of an inch.

Strength of current	Repulsion
78	78 ²
136	135 ²
184	191 ²
226	226 ²
259	259 ²
287	291 ²
341	322 ²
377	359 ²
411	386 ²

These experiments prove that, up to a strength of about 280, the attractive force operating upon the iron, and the repulsive force acting upon the bismuth, are each proportional to the square of the strength of the magnetising current. For higher powers, both attraction and repulsion increase in a smaller ratio; but it is here sufficient to show that the diamagnetic repulsion follows precisely the same law as the magnetic attraction. So accurately indeed is this parallelism observed, that while the forces at the top of the tables produce attractions and repulsions exactly equal to the square of the strength of the current, the same strength of 411, at the bottom of both tables, produces in iron an attraction of 385², and in bismuth a repulsion of 386². The numbers which indicate the strength of current in the first column are the tangents of the deflections observed in each case: neglecting the indices, the figures in the second column express the number of oscillations accomplished in a minute, multiplied by a constant factor to facilitate comparison; the forces operating upon the bars being proportional to the squares of the number of oscillations, the simple addition of the index figure completes the expression of these forces.

In these experiments the bismuth bar set across the

lines of magnetic force, while the bar of iron set *along* them ; the former was so cut from the crystalline mass, that the plane of principal cleavage was parallel to the length of the bar, and in the experiments hung vertical. I thought it interesting to examine the deportment of a bar of bismuth which should occupy the same position, with regard to the lines of force, as the bar of iron ; that is to say, which should set its length axial. Such a bar is obtained when the planes of principal cleavage are transverse to the length.

Table V.

Bar of Bismuth, No. 2.—Length 0·8 of an inch ; width 0·13 of an inch ; depth 0·15 of an inch.

Set axial between the excited poles.

Strength of current	Repulsion
68	67 ²
182	187 ²
218	218 ²
248	249 ²
274	273 ²
315	309 ¹
364	350 ²
401	366 ²

A deportment exactly similar to that exhibited in the foregoing cases is observed here also : up to about 280 the repulsions are exactly proportional to the squares of the current strengths, and from this point forward they increase in a less ratio.

A paramagnetic substance was next examined which set its length at right angles to the lines of magnetic force : the substance was carbonate of iron. The native crystallised mineral was reduced to powder in a mortar, and the powder was compressed. It was suspended, like the bismuth, between the flat poles, with its line of compression horizontal. When the poles were excited, the compressed bar set the line of pressure from pole to pole, and consequently its length equatorial.

Table VI.

Bar of compressed Carbonate of Iron.—Length 0·95 of an inch ; width 0·17 of an inch ; depth 0·23 of an inch.

Set equatorial between the excited Poles.

Strength of current	Attraction
74	74 ²
135	133 ²
179	180 ²
214	218 ²
249	248 ²
277	280 ²
341	330 ²
381	353 ²

It is needless to remark upon the perfect similarity of deportment here exhibited to the cases previously recorded.

In experiments made with bars of sulphate of iron the same law of increase was observed.

These experiments can leave little doubt upon the mind, that if a magnetic body be attracted in virtue of its being converted into a magnet, a diamagnetic body is repelled *in virtue of its being converted into a diamagnet*. On no other assumption can it be explained, why the repulsion of the diamagnetic body, like the attraction of the magnetic one, increases in a so much quicker ratio than the force of the magnet which produces the repulsion. But, as this is a point of great importance, I will here introduce corroborative evidence, derived from modes of experiment totally different from the method already described. By a series of measurements with the torsion-balance, in which the attractive and repulsive forces were determined directly, with the utmost care, the relation of the strength of the magnet to the force acting upon the following substances was found to be as follows :—

Table VII.

Spheres of Native Sulphur.

Strength of magnet	Ratio of repulsions
96	95 ²
153	158 ²
222	224 ²
265	264 ²
316	316 ²

Table VIII.

Spheres of Carbonate of Lime.

Strength of magnet	Ratio of repulsions
134	134 ²
172	173 ²
213	212 ²
259	264 ²
310	311 ²

Table IX.

Spheres of Carbonate of Iron.

Strength of magnet	Ratio of attractions
66	66 ²
89	89 ²
114	114 ²
141	141 ²

These results confirm those of M. E. Becquerel,¹ whose experiments first showed that the repulsion of diamagnetic bodies follows the same law as the attraction of magnetic ones.

Bar of Sulphur.—Length 25 millims.; weight 840 milligrms.

Squares of the magnetic intensities	Quotients of the repulsions by the magnetic intensities
36·58	0·902
27·60	0·929
26·84	0·906
16·33	0·920

The constancy of the quotient in the second column proves that the ratio of the repulsions to the squares of the magnetic intensities is a ratio of equality.

I will also cite a series of experiments by Mr. Joule,² which that excellent philosopher adduces in confirmation of the results obtained by M. E. Becquerel and myself.

Bar of Bismuth.

Strength of magnet	Repulsions
1	1 ²
2	2 ²
4	4 ²

¹ *Annales de Chimie et de Physique*, 3rd series, vol. xxviii. p. 302.

² *Phil. Mag.*, 4th series, vol. iii. p. 32.

Let us contrast these with the results obtained by Mr. Joule, on permitting the magnet to act upon a hard magnetic needle.

Magnetic Needle.—Length 1·5 of an inch.

Strength of magnet	Attraction
1	1
2	2
4	4

Here we find experiment in strict accordance with the theoretical deduction stated at the commencement of the present chapter. The intensity of the magnetism of the steel needle is constant, for the steel resists magnetisation by influence; the consequence is that the attraction is simply proportional to the strength of the magnet.

A consideration of the evidence thus adduced from independent sources, and obtained by different methods, must, I imagine, render the conclusion certain that diamagnetic bodies, like magnetic ones, exhibit their phenomena in virtue of a state of magnetisation induced in them by the influencing magnet. This conclusion is in no way invalidated by the recent researches of Plücker, on the law of induction in paramagnetic and diamagnetic bodies, but, on the contrary, derives support from his experiments. With current strengths which stand in the ratio of 1 : 2, Plücker finds the repulsion of bismuth to be as 1 : 3·62, which, though it falls short of the ratio of 1 : 4, as the law of increase according to the square of the current would have it, suffices to show that the bismuth was not passive, but acted the part of an induced diamagnet in the experiments. In the case of the iron itself, Plücker finds a far greater divergence; for here currents which stand in the ratio of 1 : 2 produce attractions only in the ratio of 1 : 2·76.

2. *Duality of Diamagnetic Excitement.*

Having thus safely established the fact that diamag-

netic bodies are repelled, in virtue of a certain state into which they are cast by the influencing magnet, the next step of our inquiry is :—Will the state evoked by one magnetic pole facilitate, or prevent, the repulsion of the diamagnetic body by a second pole of an opposite quality? If the force of repulsion were an action on the mass, considered as ordinary matter, this mass, being repelled by both the north and the south pole of a magnet, when they operate upon it separately, ought to be repelled by the sum of the forces of the two poles where they act upon it together. But if the excitation of diamagnetic bodies be of a *dual* nature, as is the case with the magnetic bodies, then it may be expected that the state excited by one pole will not facilitate, but on the contrary prevent, the repulsion of the mass by a second opposite pole.

To solve this question the apparatus sketched in fig. 5a, Plate II. was made use of. AB and CD are two helices of copper wire 12 inches long, of 2 inches internal, and of $5\frac{1}{2}$ inches external diameter. Into them fit soft iron cores 2 inches thick: the cores are bent as in the figure, and reduced to flat surfaces along the line ef, so that when the two semicylindrical ends are placed together, they constitute a cylinder of the same diameter as the cores within the helices.¹ In front of these poles a bar of pure bismuth gh was suspended by cocoon silk; by imparting a little torsion to the fibre, the end of the bar was caused to press gently against a plate of glass ik, which stood between it and the magnets. By means of a current reverser the polarity of one of the cores could be changed at pleasure; thus it was in the experimenter's power to excite the cores, so that the poles pp' should be of the same quality, or of opposite qualities.

The bar, being held in contact with the glass by a very

¹ The ends of the semicylinders were turned so as to present the apex of a truncated cone to the suspended bar of bismuth.

feeble torsion, a current was sent round the cores, so that they presented two poles of the same name to the suspended bismuth; the latter was promptly repelled, and receded to the position dotted in the figure. On interrupting the current it returned to the glass as before. The cores were next excited, so that two poles of opposite qualities acted upon the bismuth; the latter remained perfectly unmoved.¹

This experiment shows that the state, whatever it may be, into which bismuth is cast by one pole, so far from being favourable to the action of the opposite pole, completely neutralises the effect of the latter. A perfect analogy is thus established between the deportment of the bismuth and that of iron under the same circumstances; for it is well known that a similar neutralisation occurs in the latter case. If the repulsion depended upon the *strength* of the poles, without reference to their *quality*, the repulsion, when the poles are of opposite names, ought to be *greater* than when they are alike; for in the former case the poles are greatly strengthened by their mutual inductive action, while, in the latter case, they are enfeebled by the same cause. But the fact of the repulsion being dependent on the quality of the pole, demonstrates that the substance is capable of assuming a condition peculiar to each pole, or in other words, is capable of a *dual* excitation.²

¹ A shorter bar of bismuth than that here sketched, with a light index attached to it, makes the repulsion more evident. It may be thus rendered visible throughout a large lecture-room.

² Since the above was written, the opinion has been expressed to me, that the action of the *unlike* poles, in the experiment before us, is 'diverted' from the bismuth upon each other, the absence of repulsion being due to this diversion, and not to the neutralisation of inductions in the mass of the bismuth itself. Many, however, will be influenced by the argument as stated in the text, who would not accept the interpretation referred to in this note; I therefore let the argument stand, and hope at no distant day to return to the subject.—J. T. May 5, 1855.

The experiments from which these conclusions are drawn are a manifest corroboration of those made by M. Reich with steel magnets.

If we suppose the flat surfaces of the two semicylinders which constitute the ends of the cores to be in contact, and the cores so excited that the poles P and P' are of different qualities, the arrangement, it is evident, forms a true electro-magnet of the horseshoe form; and here the pertinency of a remark made by M. Poggendorff, with his usual clearness of perception, becomes manifest; namely, that if the repulsion of diamagnetic bodies be an indifferent one of the mass merely, there is no reason why they should not be repelled by the centre of a magnet, as well as by its ends.

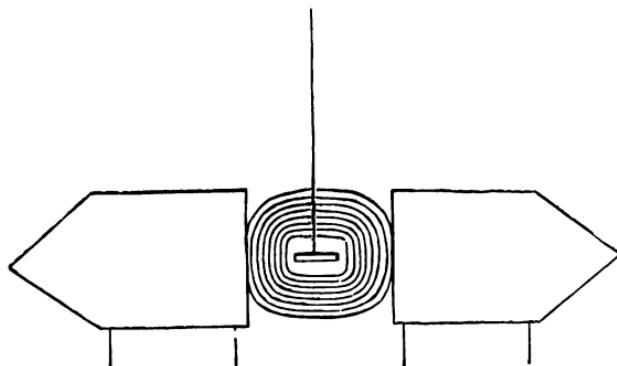
3. Separate and joint action of a Magnet and a Voltaic Current on Paramagnetic and Diamagnetic Bodies.

In operating upon bars of bismuth with the magnet, or the current, or both combined, it was soon found that the gravest mistakes might be committed if the question of molecular structure was not attended to; that it is not more indefinite to speak of the volume of a gas without giving its temperature, than to speak of the deportment of bismuth without stating the relation of the form of the mass to the planes of crystallisation. Cut in one direction, a bar of bismuth will set its length parallel to an electric current passing near it; cut in another direction, it will set its length perpendicular to the same current. It was necessary to study the deportment of both of these bars separately.

A helix was formed of covered copper wire one-twentieth of an inch thick: the space within the helix was rectangular, and was 1 inch long, 0.7 inch high, and 1 inch wide: the external diameter of the helix was 3 inches. Within the rectangular space the body to be ex-

amined was suspended by a fibre which descended through a slit in the helix. The latter was placed between the two flat poles of an electro-magnet, and could thus be caused to act upon the bar within it, either alone or in

FIG. 6.



combination with the magnet. The disposition will be at once understood from fig. 6, which gives a front view of the arrangement.

a.—Action of Magnet alone: Division of bars into Normal and Abnormal.

A bar of soft iron suspended in the magnetic field will set its longest dimension from pole to pole: this is the normal deportment of paramagnetic bodies. A bar of bismuth, whose planes of principal cleavage are throughout parallel to its length, suspended in the magnetic field with the said planes vertical, will set its longest dimension at right angles to the line joining the poles: this is the normal deportment of diamagnetic bodies. We will, therefore, for the sake of distinction, call the former a *normal paramagnetic bar*, and the latter a *normal diamagnetic bar*.

A bar of compressed carbonate of iron dust, whose

shortest dimension coincides with the line of pressure, will, when suspended in the magnetic field with the said line horizontal, set its length equatorial. A bar of compressed bismuth dust, similarly suspended, or a bar of bismuth whose principal planes of crystallisation are transverse to its length, will set its length axial in the magnetic field. We will call the former of these an *abnormal paramagnetic bar*, and the latter an *abnormal diamagnetic bar*.

b.—*Action of Current alone on normal and abnormal bars.*

A normal paramagnetic bar was suspended in the helix above described; when a current was sent through the latter, the bar set its longest horizontal dimension parallel to the axis of the helix, and consequently perpendicular to the coils.

An abnormal paramagnetic bar was suspended in the same manner; when a current was sent through the helix, the bar set its longest dimension perpendicular to the axis of the helix, and consequently parallel to the coils.

A normal diamagnetic bar was delicately suspended in the same helix; on the passage of the current it acted precisely as the abnormal magnetic bar; setting its longest dimension perpendicular to the axis of the helix and parallel to the coils. Skill is needed, but when a fine fibre and sufficient power are made use of, this deportment is obtained without difficulty.

An abnormal diamagnetic bar was suspended as above; on the passage of the current it acted precisely as the normal magnetic bar: it set its length parallel to the axis of the helix and perpendicular to the coils. Here also, by fine manipulation, the result is obtained with ease and certainty.

c.—*Action of Magnet and Current combined.*

In examining this subject, eight experiments were made with each bar; it will be remembered that fig. 6 gives a view of the arrangement in vertical section.

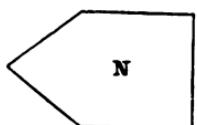
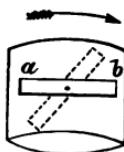
1. Four experiments were made in which the *magnet* was excited first, and after the suspended bar had taken up its position of equilibrium, the deflection produced by the passage of a current through the surrounding helix was observed.

2. Four experiments were made in which the *helix* was excited first; and when the bar within it had taken up its position of equilibrium, the magnetism was developed and the consequent deflection observed.

Normal Paramagnetic Bar.

In experimenting with iron it was necessary to place it at some distance from the magnet, otherwise the attraction of the entire mass by one or the other pole would completely mask the action sought. Fig. 7 represents, in

FIG. 7.



plan, the disposition of things in these experiments: N and S indicate the north and south poles of the magnet;

a b is the bar of iron; the helix within which the bar was suspended is shown in outline around it; the arrow shows the direction of the current in the *upper half* of the helix; its direction in the under half would, of course, be the reverse.

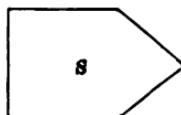
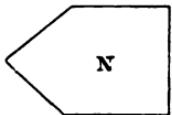
On exciting the magnet, the bar of iron set itself parallel to the line joining the poles, as shown by the unbroken line in fig. 7.

When the direction of the current in the helix was that indicated by the arrow, the bar was deflected towards the position dotted in the figure.

Interrupting the current in the helix, and permitting the magnet to remain excited, the bar returned to its former position: the current was now sent through the helix in the direction of the arrow, fig. 8; the consequent deflection was towards the dotted position.

Both the current which excited the magnet and that which passed through the helix were now interrupted, and

FIG. 8.

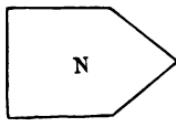
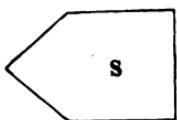
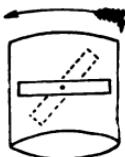


the polarity of the magnet was reversed. On sending a current through the helix in the direction of the arrow, the bar was deflected from the position of the defined line to that of the dotted one, fig. 9.

Interrupting the current through the helix, and permitting the bar to come to rest under the influence of the

magnet alone, a current was sent through the helix in a

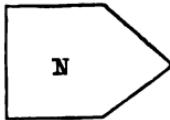
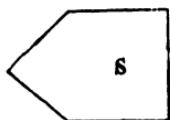
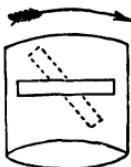
FIG. 9.



direction opposed to its former one: the deflection (from full to dotted outline) was that shown in fig. 10.

The oblique position of equilibrium finally assumed by the bar depends, of course, upon the ratio of the forces

FIG. 10.

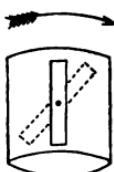


acting upon it: in these experiments, the bar, in its final position, enclosed an angle of about 50 degrees with the axial line.

A series of experiments was next made, in which the

bar was first acted on by the current passing through the helix, the magnet being brought to bear upon it afterwards. On the passage of the current through the helix in the direction shown in fig. 11, the bar set its length parallel to the axis of the latter. On exciting the magnet

FIG. 11.



so that its polarity was that indicated by the letters N and S in the figure, the deflection was towards the dotted position.

Interrupting the current through both magnet and helix, and reversing the current through the latter, the bar came to rest, as before, parallel to the axis: on exciting

FIG. 12.

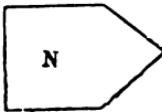
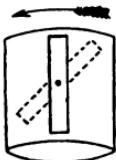


the magnet, as in the last case, the deflection was that shown in fig. 12.

Preserving the same current in the helix, and reversing

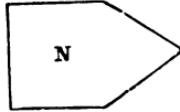
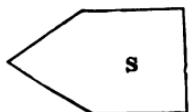
the polarity of the magnet, the deflection was that shown in fig. 13.

FIG. 13.



Preserving the magnet-poles as in the last experiment, and reversing the current in the helix, the deflection was that shown in fig. 14.

FIG. 14.



Thus far the results might, of course, have been predicted; but I am anxious to go through all the phases of this disputed question, with the view of rendering the comparison of paramagnetism and diamagnetism complete, and the inference from experiment certain.

Normal Diamagnetic Bar.

Our next step is to compare with these effects the deportment of a normal diamagnetic body placed under the same conditions.



With the view of increasing the force, the helix was removed from its lateral position and placed between the two poles, as in fig. 6, p. 146. The normal diamagnetic bar was suspended within the helix and submitted to the self-same mode of examination as that applied in the case of the paramagnetic body.

The polarity first excited was that shown by the letters *s* and *n* (south and north) in fig. 9, Plate I., and the position of rest, when the magnet alone acted, was at right angles to the line joining the poles, as shown in unbroken outline; on sending a current through the helix in the direction of the arrow, the deflection was towards the position dotted out.

Preserving the magnetic polarity as in the last experiment, the direction of the current through the helix was reversed, and the deflection was that shown in fig. 10, Plate I. [In all cases the motion is to be regarded as taking place *from* the position shown by the full line *to* that shown by the dotted line.]

Reversing the polarity of the magnet, and sending the current through the helix in the direction of the last experiment, the deflection was that shown in fig. 11.

Preserving the last magnetic poles, and sending the current through the helix in the opposite direction, the deflection was that shown in fig. 12.

In the following four experiments the helix was excited first.

Operated upon by the helix alone, the suspended bar set its length parallel to the convolutions, and perpendicular to the axis of the coil, as shown by the unbroken outline: the direction of the current was first that shown in fig. 13, Plate Ia. When the magnet was excited, the bar was deflected towards the dotted position.

Interrupting both currents and permitting the bar to

come to rest, then reversing the current in the helix, the bar set as before parallel to the coils. When the magnet was excited, as in the last experiment, the deflection was that shown in fig. 14.

Preserving the helix current as in the last experiment, when the polarity of the magnet was reversed, the deflection was that shown in fig. 15.

Interrupting both, and reversing the current in the helix; when the magnet was excited as in the last experiment, the deflection was that shown in fig. 16.

In a paper on the ‘Polarity of Bismuth,’ published in the ‘Philosophical Magazine,’ ser. 4, vol. ii., and in Poggendorff’s *Annalen*, vol. lxxxvii., an experiment of mine is recorded showing the deportment exhibited by fig. 11, Plate I. of the present series. In a recent memoir on the same subject, M. v. Feilitzsch¹ states that he has sought this result in vain. Sometimes he observed the deflection at the moment of closing the circuit, but conceived that it must be ascribed to the action of induced currents; for immediately afterwards a deflection in the opposite direction was observed, which deflection proved to be the permanent one.

I have repeated the experiment here referred to with all possible care; and the result is certainly that described in the remarks which refer to fig. 11. This result agrees in all respects with that described in my former paper. With a view to quantitative measurement, a small graduated circle was constructed and placed underneath the bar of bismuth suspended within the helix. The effect, as will be seen, is not one regarding which a mistake could be made on account of its minuteness: operating delicately, and choosing a suitable relation between the strength of

¹ Poggendorff’s *Annalen*, vol. xcii. p. 395.

the magnet and that of the helix,¹ on sending a current through the latter as in fig. 11, the bismuth bar was deflected so forcibly that the limit of its first impulsion reached 120° on the graduated circle underneath. [An action entirely due to the extreme caution bestowed upon the experiment, in which *power* and *delicacy* were combined.] The permanent deflection of the bar amounted to 60° in the same direction, and hence the deportment could in no wise be ascribed to induced currents, which vanish immediately. Before sending the current through the helix, the bar was acted on by the magnet alone, and pointed to zero.

Though it was not likely that the shape of the poles could have any influence here, I repeated the experiment, using the hemispherical ends of two soft iron cores as poles: the result was the same.

A pair of poles with the right and left-hand edges rounded off showed the same deportment.

A pair of poles presenting chisel edges to the helix showed the same deportment.

Various other poles were made use of, some of which appeared to correspond exactly with those figured by M. v. Feilitzsch; but no deviation from the described deportment was observed. To test the polarity of the magnet, a magnetic needle was always at hand: once or twice the polarity of the needle became reversed, which, had it not been noticed in time, would have introduced confusion into the experiments. Here is a source of error against which, however, M. v. Feilitzsch has probably guarded himself. Some irregularity of crystalline structure may also have influenced the result. With 'chemically pure zinc' M. v. Feilitzsch obtained the same deflection that I

¹ In most of these experiments the helix was excited by ten cells, the magnet by two.

obtained with bismuth: now chemically pure zinc is *diamagnetic*,¹ and hence its deportment is corroborative of that which I have observed. M. v. Feilitzsch, however, appears to regard the zinc used by him as magnetic; but if this be the case, it cannot have been chemically pure. It is necessary to remark that I have called the north pole of the electro-magnet that which attracts the south, or unmarked end of a magnetic needle; and I believe this is the custom throughout Germany.

Abnormal Paramagnetic Bar.

This bar consisted of compressed carbonate of iron dust, and was suspended within the helix with the line of compression, which was its shortest dimension, horizontal. As in the cases already described, it was first acted upon by the magnet alone. Having attained its position of equilibrium, a current was sent through the helix, and the subsequent deflection was observed.

The magnet being excited as shown by the letters s and n in fig. 17, Plate I., the bar sets its length equatorial; on sending a current through the helix in the direction of the arrow, the bar was deflected to the dotted position.

Reversing the current in the helix, but permitting the magnet to remain as before, the deflection was that shown in fig. 18.

Interrupting all, and reversing the polarity of the magnet; on sending the current through as in the last case, the deflection was that shown in fig. 19.

Reversing the current, but preserving the last condition of the magnet, the deflection was that shown in fig. 20,

In the subsequent four experiments the helix was excited first.

¹ Phil. Mag. vol. xxviii. p. 456.

Normal Paramagnetic Bar. *Abnormal Diamagnetic Bar.* *Paramagnetic Bar.* *Abnormal Diamagnetic Bar.*

Magnet excited first.

Diamagnetic Bar.

Helix excited first.

Normal

Paramagnetic Bar.

Helix excited first.

Abnormal

Diamagnetic Bar.

Magnet excited first.

Abnormal

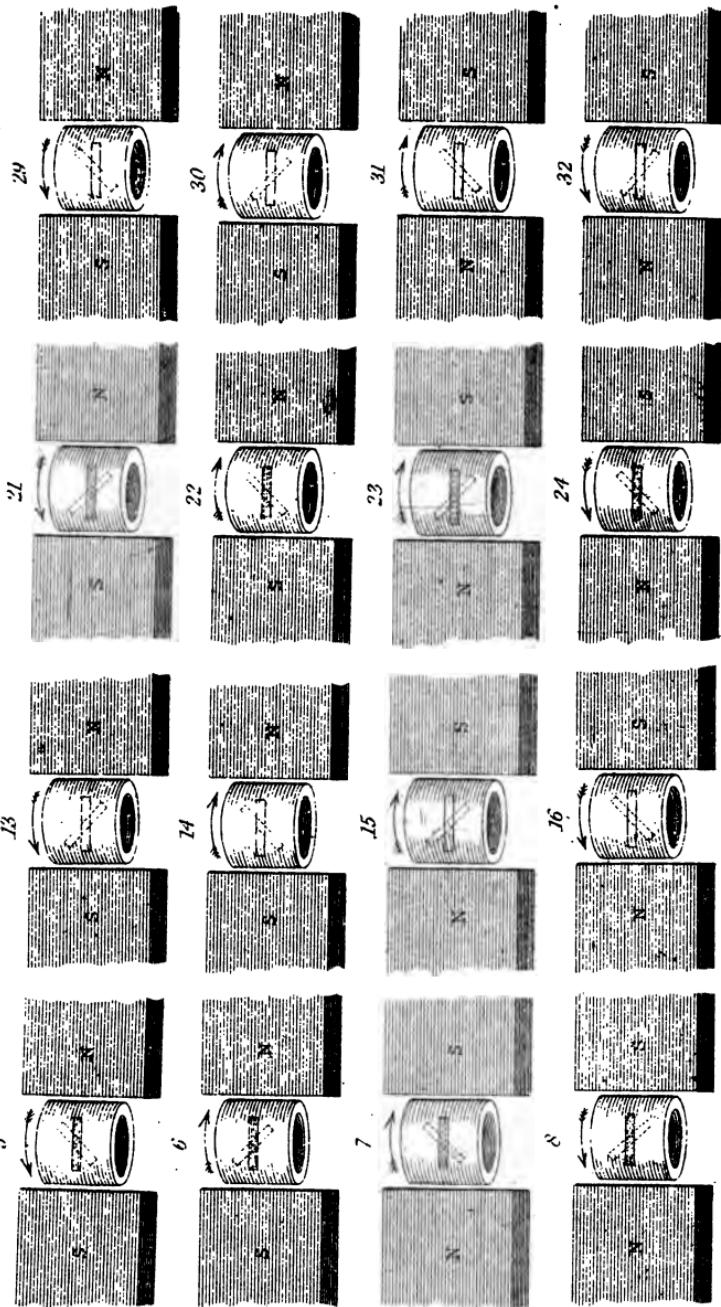
Diamagnetic Bar.

Magnet excited first.

Abnormal

Diamagnetic Bar.

Magnet excited first.



It is to be remembered that whatever might be the direction of the current through the helix alone, the bar always set its length perpendicular to the axis of the latter, and parallel to the coils.

When the direction of the helix current, and the polarity of the magnet, were those shown in fig. 21, Plate Ia, the deflection was to the dotted position.

Interrupting all, and reversing the current in the helix; on exciting the magnet the deflection was that shown in fig. 22.

Changing the polarity of the magnet, and preserving the helix current in its former direction, the deflection was that shown in fig. 23.

Interrupting all, and reversing the current through the helix; when the magnetism was developed the deflection was that shown in fig. 24.

Abnormal Diamagnetic Bar.

This bar consisted of a prism of bismuth whose principal planes of crystallisation were perpendicular to its length: the mode of experiment was the same as that applied in the other cases.

Acted upon by the magnet alone, the bar set its length from pole to pole: the magnetic excitation being that denoted by the letters N S, fig. 29, Plate Ia, a current was sent through the helix in the direction of the arrow; the bar was deflected to the dotted position.

Reversing the current through the helix, the deflection was that shown in fig. 30.

Interrupting both currents and reversing the magnetic poles; on sending a current through the helix as in the last experiment, the deflection was that shown in fig. 31.

Reversing the current through the helix, the deflection was that shown in fig. 32.

In the subsequent four experiments the helix was excited first.

Sending a current through the helix in the direction denoted by the arrow, the bar set its length at right angles to the convolutions, and parallel to the axis of the helix ; when the magnetism was excited as in fig. 25, Plate I., the deflection was to the dotted position.

When the current was sent through the helix in an opposite direction, the deflection was that shown in fig. 26.

Interrupting both currents, and reversing the poles of the magnet ; on sending a current through the helix as in the last experiment, the deflection was that shown in fig. 27.

Reversing the current in the helix, the deflection was that shown in fig. 28.

In all these cases the position of equilibrium due to the first force was attained before the second force was permitted to act.

It will be observed, on comparing the deportment of the normal paramagnetic bar with that of the normal diamagnetic one, that the position of equilibrium taken up by the latter, when operated on by the helix alone, is the same as that taken up by the former when acted on by the magnet alone : in both cases the position is from pole to pole of the magnet. A similar remark applies to the abnormal para- and diamagnetic bars. It will render the distinction between the deportment of both classes of bodies more evident, if the position of the two bars, before the application of the second force, be rendered one and the same. When both the bars, acted on by one of the forces, are axial, or both equatorial, the contrast or coincidence, as the case may be, of the deflections from this common position, by the second force, will be strikingly manifest.

To effect the comparison in the manner here indicated, the figures have been collected together and arranged upon Plate I. and Plate Ia. The first column represents the deportment of the normal paramagnetic bar under all the conditions described; the second column, that of the normal diamagnetic bar; the third shows the deportment of the abnormal paramagnetic bar, and the fourth that of the abnormal diamagnetic bar.

A comparison of the first two columns shows us that the deportment of the normal magnetic bar is perfectly antithetical to that of the normal diamagnetic one. When, on the application of the second force, an end of the former is deflected to the right, the same end of the latter is deflected to the left. When the position of equilibrium of the magnetic bar, under the joint action of the two forces, is from N.E. to S.W., then the position of equilibrium for the diamagnetic bar is invariably from N.W. to S.E. There is no exception to this antithesis, and I have been thus careful to vary the conditions of experiment in all possible ways, on account of the divergent results obtained by other inquirers. In his recent memoirs upon this subject M. v. Feilitzsch states that he has found the deflection of diamagnetic bodies, under the circumstances here described, to be precisely the same as that of paramagnetic bodies: this result is of course opposed to mine; but when it is remembered that the learned German worked confessedly with the 'roughest apparatus,' and possessed no means of eliminating the effects of structure, there seems little difficulty in referring the discrepancy between us to its proper cause.

The same perfect antithesis will be observed in the case of the abnormal bars, on a comparison of the third and fourth columns. In all cases then, whether we apply the magnet singly, or the current singly, or the magnet and current combined, the deportment of the normal dia-

magnetic bar is opposed to that of the normal paramagnetic one, and the deportment of the abnormal paramagnetic bar is opposed to that of the abnormal diamagnetic one. But if we compare the normal paramagnetic with the abnormal diamagnetic bar, we see that the deportment of the one is identical with that of the other.¹ The same identity of action is observed when the normal diamagnetic bar is compared with the abnormal paramagnetic one. The necessity of taking molecular structure into account in experiments of this nature could not, I think, be more strikingly exhibited.

For each of the bars, under the operation of the two forces, there is an oblique position of equilibrium : on the application of the second force, the bar swings like a pendulum beyond this position, oscillates through it, and finally comes to rest there. Hence, if before the application of the second force the bar occupy the axial position, the deflection, when the second force is applied, appears to be from the axis to the equator ; but if it first occupy the equatorial position, the deflection appears to be from the equator to the axis.

It has been already shown that the repulsion of diamagnetic bodies is to be referred to a state of excitement induced by the magnet, and it has been long known that the attraction of paramagnetic bodies is due to the same cause. The experiments just described exhibit to us bars of both classes of bodies moving in the magnetic field : such motions occur in virtue of the induced state of the

¹ Identical to the eye, but not to the mind. The notion appears to be entertained by some, that, by changing molecular structure, I had actually converted paramagnetic substances into diamagnetic ones, and *vice versa*. No such change, however, can cause the *mass* of a diamagnetic body suspended by its centre of gravity to be *attracted*, or the mass of a paramagnetic body to be *repelled*. But by a change of molecular structure, one of the forces may be so caused to apply itself that it shall present to the eye all the *directive* phenomena exhibited by the other.—J. T., May 5, 1855.

body, and the relation of that state to the forces which act upon it. We have seen that in all cases the antithesis between both classes of bodies is maintained. Whatever, therefore, the state of the paramagnetic bar under magnetic excitement may be, a precisely antithetical state would produce all the phenomena of the diamagnetic bar. If the bar of iron be polar, a reverse polarity on the part of bismuth would produce the effects observed. From this point of view all the movements of diamagnetic bodies become perfectly intelligible, and the experiments to be recorded in the next chapter are not calculated to invalidate the conclusion that diamagnetic bodies possess a polarity opposed to that of magnetic ones.

The phenomena to which we have thus far referred consist in the rotations of elongated bars about their axes of suspension. The same antithesis, however, presents itself when we compare the *motion of translation* of a paramagnetic body, within the coil, with that of a diamagnetic one. A paramagnetic sphere was attached to the end of a horizontal beam and introduced into the coil: the magnet being excited, the sphere could be made to traverse the space within the coil in various directions, by properly varying the current through the coil. A diamagnetic sphere was submitted to the same examination, and it was found that the motions of both spheres, when operated on by the same forces, were always in opposite directions.

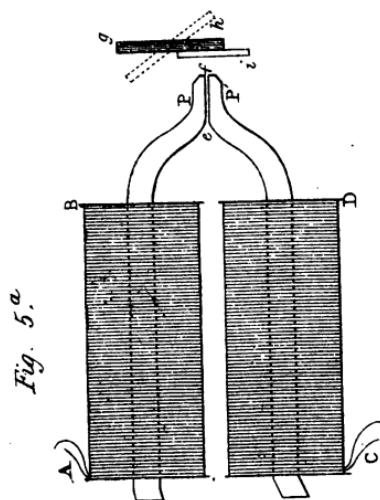
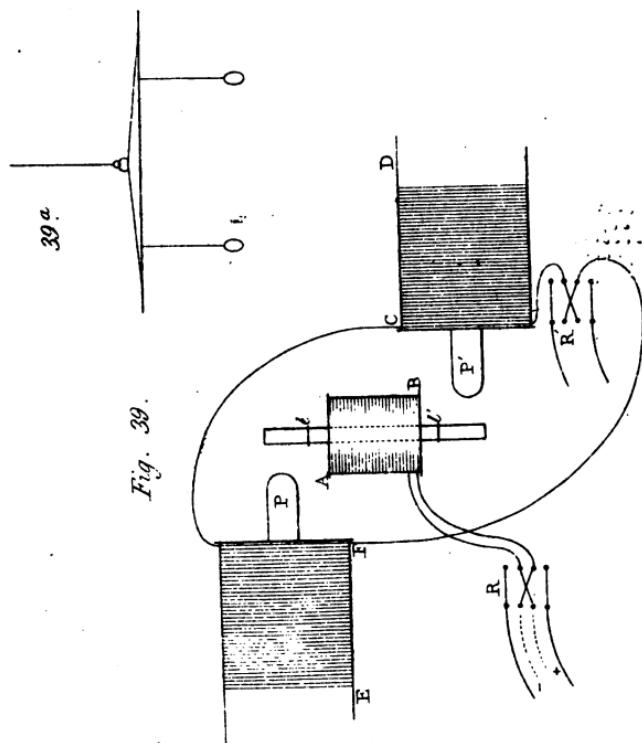
FURTHER COMPARISON OF PARAMAGNETIC AND DIAMAGNETIC PHENOMENA :—DIAMAGNETIC POLARITY.

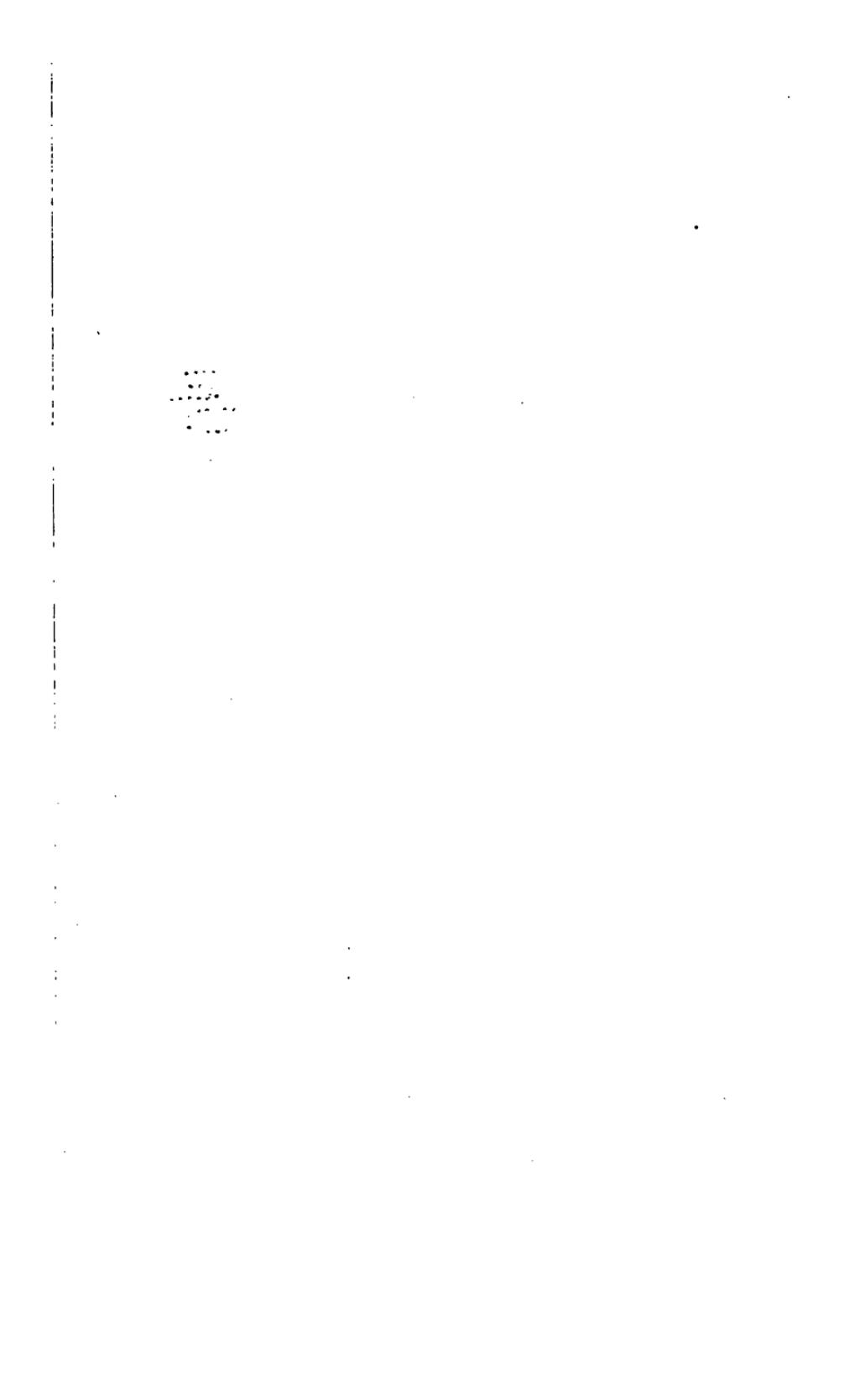
On sending a current through a helix within which is placed an iron bar, the latter is converted into a magnet, one end of the bar thus excited being attracted, and the other end repelled by the same magnetic pole.

In this *twoness* of action consists what is called the *polarity* of the bar: we will now consider whether a bar of bismuth exhibits a similar duality.

Fig. 39, Plate II. represents, in plan, the disposition of the apparatus used in the examination of this question. A B is a helix, formed of covered copper wire one-fifteenth of an inch in thickness: the length of the helix is 5 inches, the external diameter 5 inches, and internal diameter 1·5 inch. Within this helix a cylinder of bismuth $6\frac{1}{2}$ inches long and 0·4 of an inch in diameter was suspended. The suspension was effected by means of a light beam, from two points of which, sufficiently distant from each other, depended two silver wires each ending in a loop: into these loops, l'l', the bar of bismuth was introduced, and the whole was suspended by a number of fibres of unspun silk from a suitable point of support. Fig. 39a is a side view of the arrangement used for the suspension of the bar. Before introducing the bar within the helix, it was first suspended in a receiver, which protected it from air currents, and in which it remained until the torsion of the suspending fibre had exhausted itself: the bar was then removed, and the beam, without permitting the silk to twist again, was placed over the helix, the bismuth bar being then introduced through the latter, and through the wire loops. From the ends of this helix two wires passed to a current reverser R, from which they proceeded to the poles of a voltaic battery. C D and E F are two electro-magnetic helices, each 12 inches long, $5\frac{1}{2}$ inches external and 2 inches internal diameter. The wire composing them is one-tenth of an inch thick, and so coiled that the current could be sent through four wires simultaneously. Within these helices were introduced two cores of soft iron 2 inches thick and 14 inches long: the ends of the cores appear at P and P'. The helices were so connected that the same current excited both, thus developing the same magnetic strength

Plate II.





in the poles $P P'$. From the ends of the helices wires proceeded to a second current reverser r' , and thence to a second battery of considerably less power than the former. By means of the reverser r' the polarity of the cores could be changed; r' could be converted from a south pole to a north pole, at the same time that P was converted from north to south. Lastly, by a change of the connections between the two helices, the cores could be so excited as to make the poles of the same quality, both north or both south.

The diameter of the cylindrical space, within which the bismuth bar was suspended, was such as to permit of a free play of the ends of the bar through the space of an inch and a half. Having seen that the bar swung without impediment, and that its axis coincided as nearly as possible with the axis of the helix, $A B$, a current from the battery was sent through the latter. The magnetism of the cores P and r' was then excited, and the action upon the bismuth bar observed. M. v. Feilitzsch has attempted a similar experiment to that here described, but without success: when, however, sufficient power is combined with sufficient delicacy, the success is complete, and the most perfect mastery is obtained over the motions of the bar.

The helix above described as surrounding the bismuth bar is the one which I have found most convenient for these experiments; various other helices, however, were tried, with a result equally certain, if less energetic. The one first made use of was 4 inches long, 3 inches exterior diameter, and three-quarters of an inch interior diameter, with wire one-fifteenth of an inch in thickness, the bar being suspended by a fibre which passed through a slit in the helix: sending through this helix a current from a battery of ten cells, and exciting the cores by a current from one cell, the phenomena of repulsion and *attraction* were exhibited with all desirable precision.

I will now describe the results obtained by operating in the manner described. The bismuth bar being suitably suspended, a current was sent through the helix, so that the direction of the current in the *upper half* was that indicated by the arrow in fig. 40, Pl. IIa. On exciting the magnet, so that the pole N was a north pole and the pole S a south pole, the ends of the bar of bismuth were *repelled*. The final position of the bar was against the side of the helix most remote from the magnets: it is shown by dots in the figure.

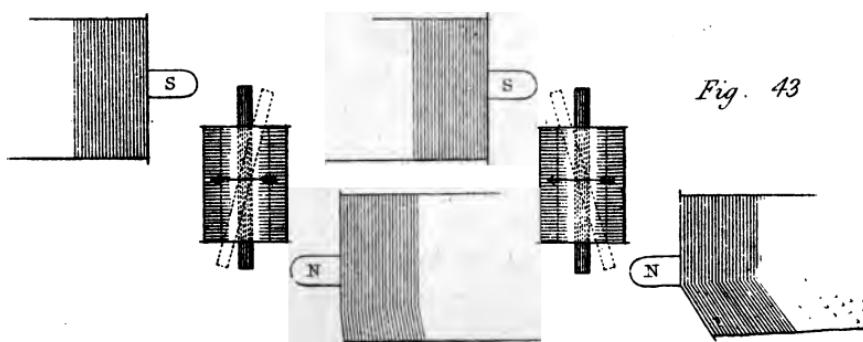
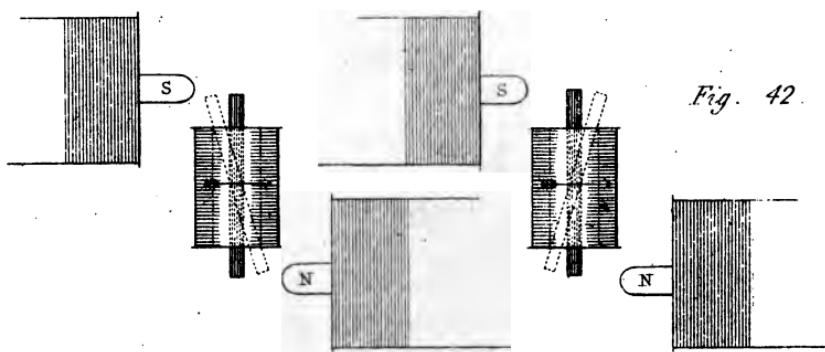
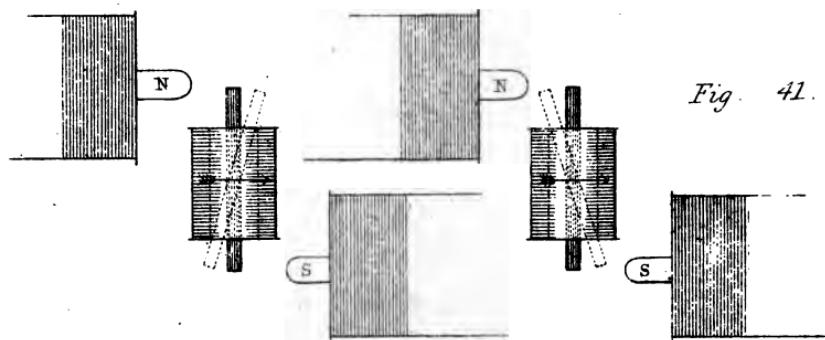
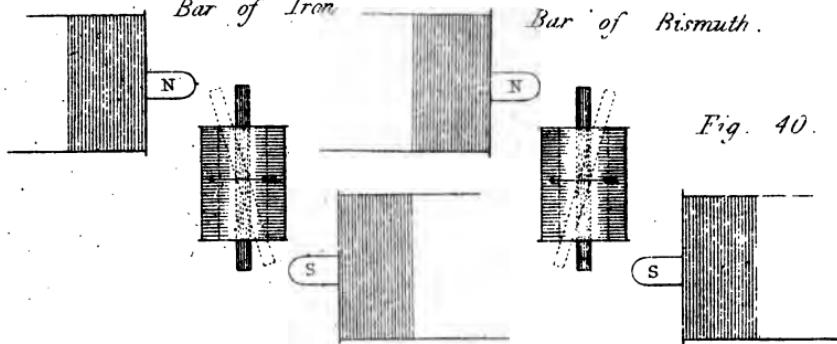
By means of the reverser R the current was now sent through the helix in the direction shown in fig. 41: the bar promptly left its position, crossed the space in which it could freely move, and came to rest as near the magnets as the side of the helix would permit it. *It was manifestly attracted by the magnets.*

Permitting the current in the helix to flow in the last direction, the polarity of the iron cores was reversed. We had then the state of things sketched in fig. 42. The bismuth bar instantly loosed from the position it formerly occupied, receded from the magnet, and took up finally the position marked by the dots.

After this new position had been attained, the current through the helix was reversed: the bar promptly sailed across the field towards the magnets, and finally came to rest in the dotted position, fig. 43. In all these cases, when the bar was freely moving in any direction, under the operation of the forces acting upon it, the reversion either of the current in the helix, or of the polarity of the cores, arrested the motion; approach was converted into recession, and recession into approach.

The ends of the helix in these experiments were not far from the ends of the soft iron cores; and it might therefore be supposed that the action was due to some modification of the cores by the helix, or of the helix by

Bar of Iron Bar of Bismuth.





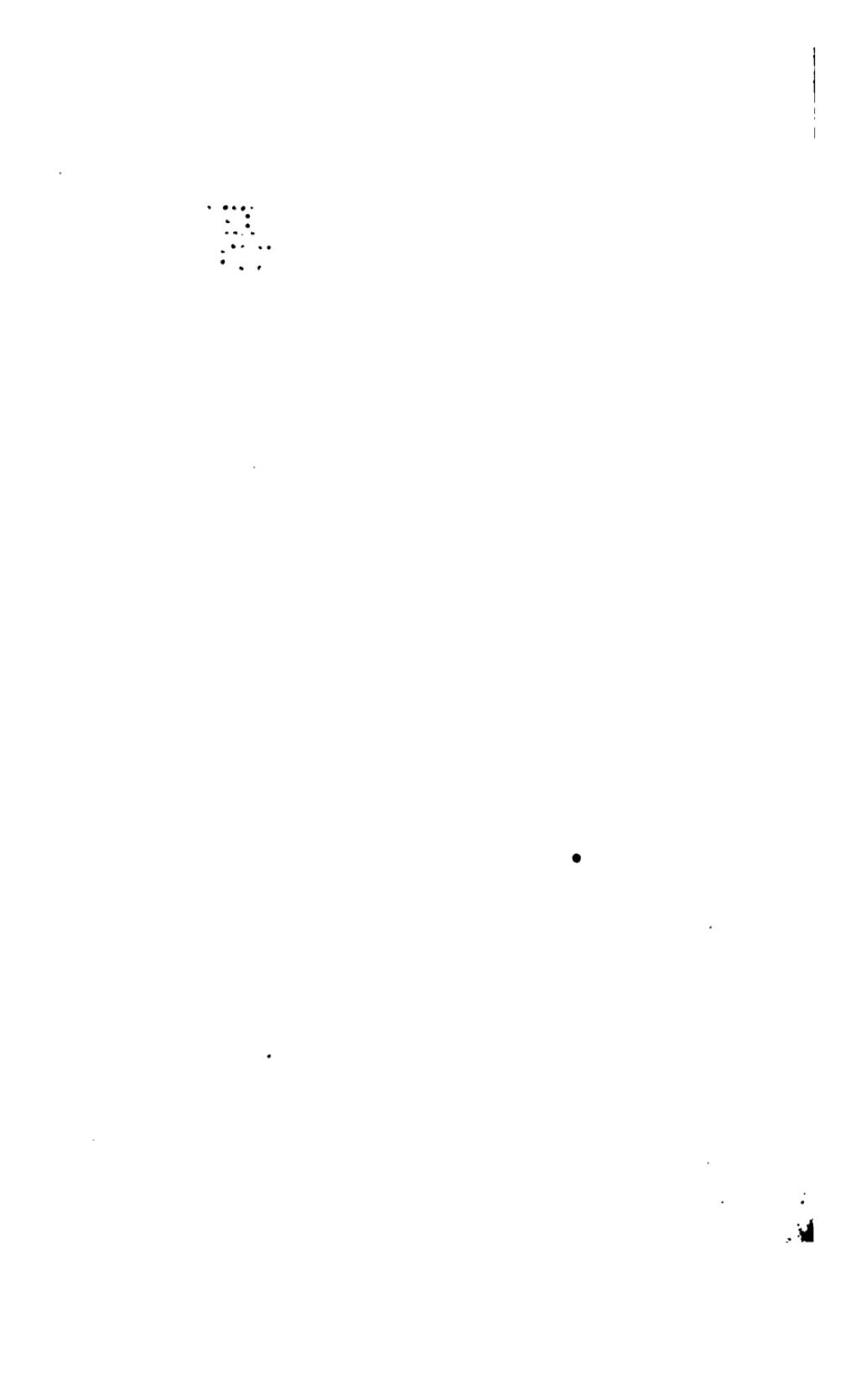
the cores. It is manifest that the magnets can have no permanent effect upon the helix; the current through the latter, measured by a tangent galvanometer, is just as strong when the cores are excited as when they are un-excited. The helix may certainly have an effect upon the cores, and this effect is either to enfeeble the magnetism of the cores or to strengthen it; but if the former, and if the bar were the simple bismuth which it is when no current operates on it, the action, though weakened, *would still be repulsive*; and if the latter, the increase would simply augment the repulsion. The fact, however, of the ends of the bar being *attracted*, proves that the bar has been thrown into a peculiar condition by the current circulating in the surrounding coil. Changing the direction of the current in the coil, we find that the self-same magnetic forces which were formerly attractive are now repulsive; to produce this effect the condition of the bar must have changed with the change of the current; or, in other words, the bar is capable of accepting *two different states* of excitement, which depend upon the direction of the current.

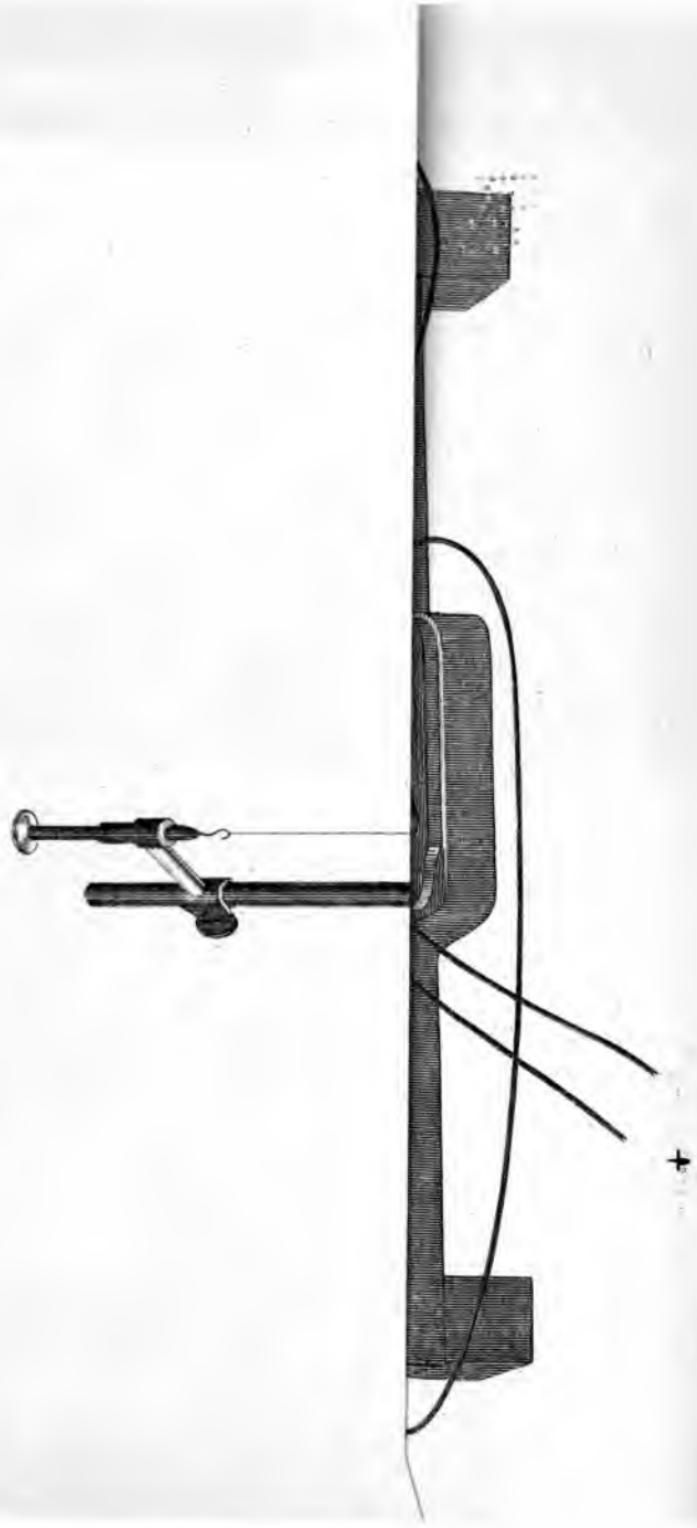
In order, however, to reduce as far as possible the action of the helix upon the cores, I repeated the experiments with the small helix referred to in fig. 6, page 146. It will be remembered that this helix is but an inch in length, and that the bismuth bar is $6\frac{1}{2}$ inches long. I removed the magnets further apart, so that the centres of the cores were half an inch beyond the ends of the bismuth bar, while the helix encircled only an inch of its central portion: in this position, when the helix was excited, there was no appreciable magnetism excited by it in the dormant cores; at least, if such were excited, it was unable to attract the smallest iron nail. Here then we had cores and helix sensibly independent of each other, but the phenomena appeared as before. The bar could

be held by the cores against the side of the helix, with its ends only a quarter of an inch distant from the ends of the cores; on reversing either of the currents the ends instantly receded, but the recession could be stopped by again changing the direction of the current. With a tranquil atmosphere, and an arrangement for reversing the current without shock or motion, the bar obeyed in an admirable manner the will of the experimenter, and, under the operation of the forces indicated, exhibited all the deflections sketched in figs. 40, 41, 42, and 43, Plate IIa.

That the motion of the bar could not be referred to the action of induced currents was readily proved. The bar was brought into the centre of the hollow cylinder in which it swung, and held there, with the forces in action, until all phenomena of induced currents had long passed away; the arrangement of the forces being that shown in fig. 40, on releasing the bar it was driven from the cores, whereas when the arrangement was that shown in fig. 41, it was drawn towards them.

But it does not sufficiently express the facts to say that the bar is capable of two different states of excitement; it must be added, that both states exist simultaneously in the excited bar. It has been already proved, that the state corresponding to the action of one pole is not that which enables an opposite pole to produce the same action; hence, when the two ends of the bar are attracted or repelled, at the same time, by two opposite poles, it is a proof that these two ends are in opposite states. But if this be correct, we can test our conclusion by reversing one of the poles: the direction of its force being thereby changed, it ought to hold the other pole in check and prevent all motion in the bar. This is the case: if, in any one of the instances cited, the polarity of either of the cores be altered; if the south be converted into a north, or the north into a south pole, thus making





both poles of the same quality, the repulsion of the one is so nearly balanced by the attraction of the other, that the bar remains without motion towards either of them.

To carry the argument a step further, let us fix our attention for an instant upon fig. 40. The end of the bar nearest to the reader is repelled by a south pole; the same end ought to be *attracted* by a north pole. In like manner, the end of the bar most distant from the reader is repelled by a north pole, and hence the state of that end ought to fit it for *attraction* by a south pole. If, therefore, our reasoning be correct, when we place a north pole opposite to the near end of the bar, and on the same side of it as the upper north pole, and a south pole opposite the further end of the bar and on the same side of it as the lower south pole, the simultaneous action of these four poles ought to be more prompt and energetic than when only two poles are used. This arrangement is shown in Plate III.: the two poles to the right of the bismuth bar must be of the same name, and the two to the left of the bar of the opposite quality. If those to the right be both north, those to the left must be both south, and *vice versa*. The current reverser for the magnets appears in front, that for the helix is hidden by the figure. The above conclusion is perfectly verified by experiments with this apparatus, and the twofold deflection of the bismuth bar is exhibited with remarkable energy.¹

The bar used in these cases is far heavier than those commonly employed in experiments on diamagnetism, but the dimensions stated do not mark the practical limit

¹ With careful manipulation these experiments, and almost all the others mentioned in this memoir, may be exhibited in the lecture-room. By attaching indexes of wood to the bars of bismuth, and protecting the indexes from air currents by glass shades, the motions may be made visible to several hundred persons at the same time. See a description of a Polymagnet, Phil. Mag., June 1855.—J. T.

of the size of the bar. A solid bismuth cylinder, 14 inches long and 1 inch in diameter, was suspended in a helix 5·7 inches long, 1·8 inch internal diameter, 4 inches external diameter, and composed of copper wire 0·1 of an inch in thickness. When a current of twenty cells was sent through the helix, and the magnets (only two of them were used) were excited by one cell, all the phenomena exhibited by figs. 40, 41, 42, and 43 were distinctly exhibited.

A considerable difference is always necessary between the strength of the current which excites the bismuth and that which excites the cores, so as to prevent the induction of the cores, which of itself would be followed by repulsion, from neutralising, or perhaps inverting, the induction of the helix. When two magnets were used and the bismuth was excited by ten cells, I found the magnetic excitement by one or two cells to be most advantageous. When the cores were excited by ten, or even five cells, the action was always repulsive.

The deportment of paramagnetic bodies is so well known, that it might be left to the reader to discern that in all the cases described it is perfectly antithetical to that of the diamagnetic body. I have nevertheless thought it worth while to make the corresponding experiments with an iron bar; and to facilitate comparison, the results are placed in Plate IIa. side by side with those obtained with the bar of bismuth. It must be left to the reader to decide whether throughout this inquiry the path of strict inductive reasoning has not been adhered to: if this be the case, then the inference appears unavoidable:—

That the diamagnetic force is a polar force, the polarity of diamagnetic bodies being opposed to that of paramagnetic ones under the same conditions of excitement.

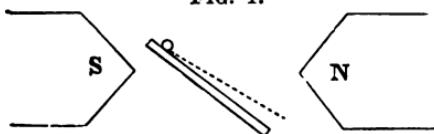
NOTE.

I would gladly refer to M. Plücker's results in connection with this subject had I been successful in obtaining them ; I will here, however, introduce the description of his most decisive experiment in his own words. (See *Scien. Mem. New Ser.* p. 336.)

' From considerations of which we shall speak afterwards, it appeared to me probable that bismuth not only assumes polarity in the vicinity of a magnetic pole, but that it also retains the polarity for some time after the excitation has taken place ; or, in other words, that bismuth retains a portion of its magnetism permanently, as steel, unlike soft iron, retains a portion of the magnetism excited in it by induction. My conjecture has been corroborated by experiment.

' I hung a bar of bismuth, 15 millims. long and 5 millims. thick, between the pointed poles of the large electro-magnet ; it was suspended horizontally from a double cocoon-thread (fig. 1). The distance between the points was diminished until the bar could barely swing freely between them. A little rod of glass was brought near to one of

FIG. 1.



the points, so that the bismuth bar, before the magnetism was excited, and in consequence of the torsion, leaned against the glass rod. On exciting the magnet by a current of three of Grove's

elements, the bismuth, prevented from assuming the equatorial position, pressed more forcibly against the glass rod ; when the current was interrupted, the bar remained still in contact with the rod, while its free end vibrated round its position of equilibrium. The current was closed anew and then reversed by a gyrotrope. In consequence of this reversion, the bar of bismuth, loosening from the glass rod, moved towards the axial position, but soon turned and pressed against the glass as before, or in some cases having passed quite through the axial position was driven round with the reversed ends into the equatorial. . . . This experiment, which was made with some care, proves that the bismuth requires time to reverse its polarity.'

I have repeated this experiment with great care, and have obtained in part the effect described : it is perfectly easy to produce the rotation of the bar. The cause of this rotation, however, was in my case as follows :—When the magnet was unexcited, the position of equilibrium of the axis of the bar acted upon by the torsion of the fibre was that shown by the dotted line in the figure ; when the magnetism was developed, the repulsive force acting on the free end of the bar necessarily pushed it beyond the dotted line—an action which was perfectly evident when the attention was directed towards it. On reversing the current, a little time was required to change the polarity of the iron

masses; during this time the free end of the bismuth *fell* towards its former position, and the velocity required was sufficient to carry it quite beyond the pole points. The only difference between M. Plücker and myself is, that I obtained the same result by simply *intercepting* the current as by reversing it. I may remark that I have submitted ordinary bismuth to the most powerful and delicate tests, but as yet I have never been able to detect in it a trace of that retentive power ascribed to it by M. Plücker.

ON W. WEBER'S THEORY OF DIAMAGNETIC POLARITY,¹ AND ON AMPÈRE'S THEORY OF MOLECULAR CURRENTS.

If we reflect upon the experiments recorded in the foregoing pages from first to last; on the inversion of magne-crystallic phenomena by the substitution of a magnetic constituent for a diamagnetic; on the analogy of the effects produced in magnetic and diamagnetic bodies by compression; on the antithesis of the rotating actions described near the commencement; on the indubitable fact that diamagnetic bodies, like magnetic ones, owe their phenomena to an induced condition into which they are thrown by the influencing magnet, and the intensity of which is a function of the magnetic strength; on the circumstance that this excitation, like that of soft iron, is of a dual character; on the numerous additional experiments which have been recorded, all tending to show the perfect antithesis between the two classes of bodies; we can hardly fail to be convinced that Faraday's first hypothesis of diamagnetic action is the true one—that diamagnetic bodies operated on by magnetic forces possess a polarity ‘the same in kind as, but the reverse in direction of that acquired by magnetic bodies.’ But if this be the case, how are we to conceive of the *physical mechanism* of this polarity? According to Coulomb's and Poisson's theory, the act of magnetisa-

Poggendorff's *Annalen*, vol. lxxxvii. p. 145, and Taylor's Scientific Memoirs, New Ser. p. 163.

tion consists in the decomposition of a neutral magnetic fluid ; the north pole of a magnet, for example, possesses an attraction for the south fluid of a piece of soft iron submitted to its influence, draws the said fluid towards it, and with it the material particles with which the fluid is associated. To account for diamagnetic phenomena this theory seems to fail altogether ; according to it, indeed, the oft-used phrase, ‘a north pole exciting a north pole, and a south pole a south pole,’ involves a contradiction. For if the north fluid be supposed to be *attracted* towards the influencing north pole, it is absurd to suppose that its presence there could produce *repulsion*. The theory of Ampère is equally at a loss to explain diamagnetic action ; for if we suppose the particles of bismuth surrounded by molecular currents, then according to all that is known of electro-dynamic laws, these currents would set themselves parallel to, and in the same direction as those of the magnet, and hence attraction, and not repulsion, would be the result. The fact, however, of this not being the case proves that these molecular currents are not the mechanism by which diamagnetic induction is effected. The consciousness of this, I doubt not, drove M. Weber to the assumption that the phenomena of diamagnetism are produced by molecular currents, not *directed*, but actually *excited* in the bismuth by the magnet. Such induced currents would, according to known laws, have a direction *opposed* to those of the inducing magnet, and hence would produce the phenomena of repulsion. To carry out the assumption here made, M. Weber is obliged to suppose that the molecules of diamagnetic bodies are surrounded by channels, in which the induced molecular currents, once excited, continue to flow without resistance.

This theory, notwithstanding its great beauty, is so extremely artificial, that I imagine the general conviction

of its truth cannot be very strong ; but there is one conclusion flowing from it which appears to me to be in direct opposition to experimental facts. The conclusion is ‘*that the magnetism of two iron particles in the line of magnetisation is increased by their reciprocal action ; but that, on the contrary, the diamagnetism of two bismuth particles lying in this direction is diminished by their reciprocal action.*’ The reciprocal action of the particles varies inversely as the cube of the distance between them ; at a distance expressed by the number 1, for example, the enfeeblement is eight times what it would be at the distance 2.

The conclusion, as regards the iron, is undoubtedly correct ; but I believe experiment proves that the mutual action of diamagnetic molecules, when caused to approach each other, *increases* their repulsive action. I have had massive iron moulds¹ made and coated with copper electrolytically ; into these fine bismuth powder has been introduced and submitted to powerful hydraulic pressure. No sensible fact can, I think, be more certain than that the particles of this dust are brought into closer proximity along the line in which the pressure is exerted, and this is the line of *strongest diamagnetisation*. If a portion of the compressed mass be placed upon the end of a torsion beam and the amount of repulsion measured, it will be found that the repulsion is a maximum when the line of magnetisation coincides with the line of compression ; or, in other words, with that line in which the particles are packed most closely together ; if the bismuth were fixed, and the magnet movable, the former would repel the latter with a maximum force when the line of compression is parallel to the direction of magnetisation. It is a stronger *diamagnet* in this direction than in any other. Cubes of bismuth which, in virtue of their crystallisation,

¹ For drawings of these moulds see a future page.

possessed a line of minimum magnetisation, have been placed in those moulds and pressed closely together in the direction of the said line: the approximation of the particles thus affected has converted the direction spoken of from one of minimum into one of maximum magnetisation. It would be difficult for me to say how many diamagnetic bodies I have submitted to compression, some massive, some in a state of powder, but in no single instance have I discovered an exception to the law that the line of compression of purely diamagnetic bodies is the line of strongest diamagnetisation. The approximation of diamagnetic particles is therefore accompanied by an augmentation of their power, instead of a diminution of it, as supposed by the theory of M. Weber.

It is scarcely possible to reflect upon the discovery of Faraday in all its bearings, without being deeply impressed with the feeling that we know absolutely nothing of the physical causes of magnetic action. We find the magnetic force producing, by processes which are evidently similar, two great classes of effects. We have a certain number of bodies which are attracted by the magnet, and a far greater number which are repelled by the same agent. Supposing these facts to have been known to Ampère, would he have satisfied his profound mind by founding a theory which accounts for only the smaller portion of them? This theory is admirable as far as it goes, but the generalisation is yet to come which shall show the true relationship of phenomena, towards whose connection the theory of Ampère furnishes at present no apparent clue.

ON M. MATTEUCCI'S OBJECTIONS.

The foregoing memoir was on the point of leaving my hands for the Royal Society, when accident, backed by the kindness of Faraday, placed the *Cours spécial*

of M. Matteucci, recently published in Paris, in my hands. An evening's perusal of this valuable work induces me to append the following remarks to the present paper.

M. Matteucci honours the researches which bear my name, and those which I published in connection with M. Knoblauch, with a considerable share of his attention. He corroborates all the experimental facts, but at the conclusion states three objections to the manner in which these facts have been explained. 'La faveur,' writes the learned Italian, 'avec laquelle les idées de MM. Tyndall et Knoblauch ont été accueillies m'imposent le devoir de ne pas vous laisser ignorer les objections qui s'élèvent contre elles. La première consiste dans la différence très-grande et constante dans la force qui fait osciller entre les pôles une aiguille de bismuth cristallisé, suivant que ses clivages parallèles à sa longueur sont suspendus verticalement ou dans un plan horizontal: cette différence me paraît inconciliable avec le résultat déjà rapporté de l'expérience de M. Tyndall, sur lequel se fonde l'explication des phénomènes magnéto-cristallisés. Mais une objection encore plus grave est celle du mouvement d'*attraction*¹ vers les pôles qui se manifeste dans les prismes de bismuth cristallisé dont les clivages sont perpendiculaires à leur longueur. Pour rendre la conséquence de cette dernière expérience encore plus évidente, j'ai fixé deux cubes de bismuth, qui ont deux faces opposées naturelles et parallèles aux plans de clivage, aux extrémités d'un petit levier de verre, ou de sulphate de chaux, suspendu par un fil de cocon au milieu du champ magnétique entre les extrémités polaires d'un électro-aimant (fig. 27a); lorsque les deux cubes ont les clivages verticaux et perpendiculaires à la longueur de l'aiguille, au moment où le circuit est

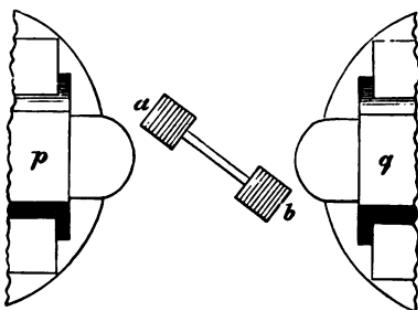
¹ This is in reality not a 'movement of *attraction*.'—See Appendix to the present paper.—J. T., May 1855.

fermé, l'aiguille est attirée, quelle que soit la position qu'elle occupe dans le champ magnétique, et se fixe en équilibre dans la ligne polaire. . . . Il me semble impossible d'expliquer ces mouvements du bismuth cristallisé, comme on a essayé de le faire, par la force répulsive de l'aimant, qui, suivant l'expérience de M. Tyndall,¹ s'exerce avec plus d'intensité parallèlement aux clivages que dans la direction perpendiculaire à ces plans.

'Remarquons encore qu'on ne trouve pas constamment l'accord qui devrait exister, selon les idées de MM. Tyndall et Knoblauch, entre les phénomènes magnéto-cristallisés et les effets produits par la compression dans le bismuth, si l'on considère ces plans de clivage et la ligne suivant laquelle la compression a eu lieu comme jouissant des mêmes propriétés.'²

With regard to the first objection I may say that it is extremely difficult to meet one so put; it is simply an opinion, and I can scarcely say more than that mine does not coincide with it. I would gladly enter upon the subject and endeavour to give the objection a scientific form were the necessary time at my disposal, but this, I regret to say, is not the case at present. I shall moreover be better pleased to deal with the objection after it has assumed a more definite form in the hands of its proposer, for I entertain no doubt that it is capable of a sufficient answer. The second objection M. Matteucci considers to

FIG. 27a.



¹ This was first proved by Mr. Faraday.—J. T.

² *Cours spécial sur l'Introduction, etc.*, p. 255.

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be a more grave one. The facts are as follows:—The repulsion of a mass of crystallised bismuth depends upon the direction in which the mass is magnetised. When the magnetising force acts in a certain direction, the intensity of magnetisation, and the consequent repulsion of the mass, is a maximum. This is proved by placing the mass upon the end of a torsion beam and bringing its several directions successively into the line of the magnetic force. Poisson would have called such a direction through the mass a principal axis of magnetic induction, and it has been elsewhere called a line of elective polarity. When a sphere or cube of bismuth is freely suspended in the magnetic field, with the direction referred to horizontal, in all positions, except two, the forces acting on the mass tend to turn it; those positions are, when the line of maximum magnetisation is axial and when it is equatorial, the former being a position of unstable, and the latter a position of stable equilibrium. When the above line is oblique to the direction of magnetisation, the sphere or cube will turn round its axis of suspension until the direction referred to has set itself at right angles to the line joining the poles. Now if the direction of maximum magnetisation be transverse to an elongated mass of bismuth, such a mass must, when the said direction recedes to the equator, sets its length from pole to pole. The facts observed by M. Matteucci seem to me to be a simple corroboration of this deduction.

The third objection is directed against an imaginary case, ‘si l'on considère les plans de clivage et la ligne de compression comme jouissant des mêmes propriétés.’ It must be evident that a crystal like bismuth, possessing a number of cleavages of unequal values, cannot be compared in all respects with a body which has suffered pressure *in one direction* only. I have no doubt whatever, that, by a proper application of pressure in different directions, a

compressed mass might be caused to imitate to perfection every one of the actions exhibited by crystallised bismuth. Indeed, I would go further, and say, that I shall be happy to undertake to reproduce, with bismuth powder, the deportment of any diamagnetic crystal whatever that M. Matteucci may think proper to name.

In looking further over M. Matteucci's instructive book, I find another point alluded to in a manner which tempts me to make a few remarks in anticipation of a fuller examination of the subject. The point refers to the reciprocal action of the particles of magnetic and diamagnetic bodies. It is easy to see, that if the attraction of a bar of iron varies simply as the number of the molecules attracted, then, inasmuch as the weight of the body varies in the same ratio, and the moment of inertia as the weight, the times of oscillation of two masses of the same length, but possessing different numbers of attracting particles, must be the same. Coulomb indeed mixed iron filings with wax, so as to remove the particles out of the sphere of their mutual inductive action, and proved that when needles of equal lengths, but of different diameters, were formed from the same mixture, the duration of an oscillation was the same for all. From this he inferred that the attractive force is simply proportional to the number of ferruginous particles; but this could not be the case if these particles exerted any sensible reciprocal action, either tending to augment or diminish the induction due to the direct action of the magnet. On account of such a mutual action, two bars of solid iron, of the same length, and of different diameters, have not the same time of oscillation.

In examining the question whether the particles of diamagnetic bodies exert a similar reciprocal action, M. Matteucci fills quills of the same length, and of different diameters, with powdered bismuth, and finds that there is



no difference between the duration of an oscillation of the thick ones and the slender ones; from this he infers that there can be no reciprocal action among the particles of the bismuth.

Now it is not to be imagined that even in Coulomb's experiments with the iron filings the molecular induction was absolutely nothing, but simply that it was so enfeebled by the separation of the particles that it was insensible in the experiments. This remark applies with still greater force to M. Matteucci's experiments with the bismuth powder; for the enfeeblement of a force already so weak, by the division of the diamagnetic mass into powder, must of course practically extinguish all reciprocal action of the particles; even supposing a weak action of the kind to exist when the mass is compact.

I will not here refer to my own experiments on compressed bismuth, but will take a result arrived at by M. Matteucci himself while repeating and corroborating these experiments. 'I made,' says M. Matteucci, 'two cylinders of bismuth precisely of the same dimensions, the one compressed, the other in its natural state, and found that the compressed mass had a diamagnetic power *distinctly superior* to that of natural bismuth.'¹ Now M. Matteucci, in his *Cours spécial*, has made his own choice of a test of reciprocal molecular action; he assumes that if cylinders of the same length, but of different masses, have equal times of oscillation, it is a conclusive proof that there is no action of the kind referred to. This necessarily implies the assumption, that were the times of oscillation *different*, a reciprocal action would be demonstrated. According to his experiments described in the Association Report, the times of oscillation *are* different; the diamagnetism of the compressed cylinder is '*distinctly su-*

¹ Report of Brit. Assoc. for 1852, Transactions of Sections, p. 7.

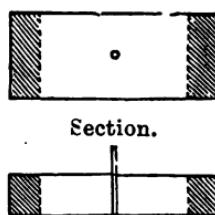
perior' to that of the uncompressed one : *the diamagnetic effect increases in a greater proportion than the quantity of matter*; and hence, on M. Matteucci's own principles, the result negatived by his experiments on powdered bismuth is fairly established by those which he has made with the compressed substance.

FURTHER REFLECTIONS.

Reflecting further on the subject of diamagnetic polarity, an experiment occurred to me which constitutes a crucial test to which the conclusions arrived at in the foregoing memoir may be submitted.

Two square prisms of bismuth, 0·43 of an inch long and 0·2 of an inch wide, were laid across the ends of a thin plate of cedar wood, and fastened there by white wax. Another similar plate of wood was laid over the prisms, and also attached to them by wax; a kind of rectangular box was thus formed, 1 inch long and of the same width as the length of the prisms, the ends of the box being formed by the latter, while its sides were open. Both plates of wood were pierced through at the centre, and in the aperture thus formed a wooden pin was fixed, which could readily be attached to a suspending fibre. Fig. 1 represents the arrangement both in plan and section.

FIG. 1.



The prisms first chosen were produced by the compression of fine bismuth powder, without the admixture of gum or any other foreign ingredient, the compressed mass being perfectly compact and presenting a surface of metallic brilliancy. Placed on the end of a torsion balance, with a magnetic pole brought to bear upon it, the repulsion of such a mass is a maximum when the direction in

which the mass has been squeezed is in the continuation of the axis of the magnet. A comparative view of the repulsion in this direction, and in another perpendicular to it, is given in the following table :—

Strength of magnet	Compressed Bismuth powder.	
	Line of pressure axial	Line of pressure equatorial Repulsion
5·8	22	13
8·4	46	31
10·0	67	46
11·9	98	67

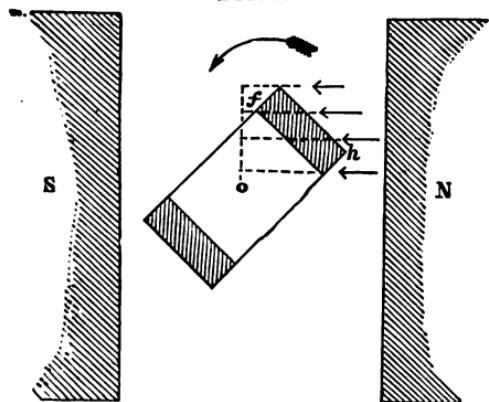
We see here that the repulsion, when the line of pressure is axial, exceeds what occurs when the same line is equatorial by fully one-half the amount of the latter. Now this can only be due to the more intense magnetisation, or rather diamagnetisation, of the bismuth along the line of pressure ; and in the experiment now to be described, I availed myself of this fact to render the effect more decided.

The prisms of bismuth were so constructed that the line of pressure was parallel to the *length* of each prism. The

rectangular box above referred to was suspended from its centre of gravity in the magnetic field, so that the two prisms were in the same horizontal plane. Let the position of the box thus suspended be that

shown in fig. 2. For the sake of simplicity, we will confine our attention to the action of one of the poles N, which

FIG. 2.



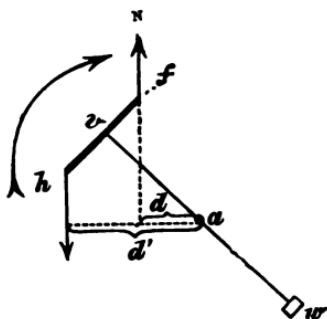
may be either flat or rounded, upon the prism hf adjacent to it, as indeed all the phenomena to be described can be produced before a single pole. The direction of the force emanating from N is represented by the arrows; and if this force be *purely repulsive*, the action upon every single particle of the diamagnetic mass furnishes a ‘moment’ which, in the position here assumed, tends to turn the rectangular box in the direction marked by the full arrow above. *It is perfectly impossible that such a system of forces could cause the box to turn in a direction opposed to the arrow; yet this is the direction in which the box turns when the magnetic force is developed.*

Here, then, we have a mechanical effect which is absolutely inexplicable on the supposition that the diamagnetic force is purely repulsive. But if the conclusions arrived at in the foregoing memoir be correct, if the diamagnetic force be a polar force, then we must assume that attraction and repulsion are developed simultaneously, as in the case of ordinary magnetic phenomena. Let us examine how this assumption will affect the analysis of the experiment before us.

The marked end of a magnetic needle is pulled towards the north magnetic pole of the earth; and yet, if the needle be caused to float upon a liquid, there is no motion of its mass towards the terrestrial pole referred to. The reason of this is known to be, that the south end of the needle is repelled by a force equal to that by which the north, or marked end, is attracted. These two equal and opposite forces destroy each other as regards *a motion of translation*, but they are effective in producing *a motion of rotation*. The magnetic needle, indeed, when in a position oblique to the plane of the magnetic meridian, is solicited towards that plane by a mechanical couple, and if free to move, will turn and find its position of equilibrium there.

Let such a needle, fh , be attached, as in fig. 3, to the end of a light wooden beam, vw ; let the beam and needle

FIG. 3.



be suspended horizontally from the point a , round which the whole system is free to turn, the weight of the needle being balanced by a suitable counterpoise, w ; let the north pole of the earth be towards n . Supposing the beam to occupy a position oblique to the magnetic meridian, as in the figure,

the end f , or the marked end, of the needle is solicited towards n by a force ϕ , and the tendency of this force to produce rotation in the direction of the arrow is expressed by the product of ϕ into the perpendicular drawn from the centre of suspension a to the line of direction of the force. Setting this distance = d , we have the moment of ϕ in the direction stated,

$$= \phi d.$$

The end h of the needle is repelled by the magnetic pole n with a force ϕ' : calling the distance of the direction of this latter force from the axis of rotation, d' , we have the moment of ϕ' in a direction opposed to the arrow,

$$= \phi' d'.$$

Now as the length of the needle may be considered a vanishing quantity as compared with its distance from the terrestrial pole, we have practically

$$\phi = \phi',$$

and consequently, as d is less than d' ,

$$\phi d < \phi' d'.$$

The tendency to turn the lever in a direction opposed to the arrow is therefore predominant; the lever will obey

this tendency, and move until the needle finds itself in the magnetic meridian; when this position is attained, the predominance spoken of evidently ceases, and the system will be in equilibrium. Experiment perfectly corroborates this theoretic deduction.

In this case, the centre of gravity of the needle recedes from the north magnetic pole as if it were repelled by the latter; but it is evident that the recession is not due either to the attraction or repulsion of the needle considered as a whole, but simply to the mechanical advantage possessed by the force ϕ' , on account of its greater distance from the axis of rotation. If the force acting upon every particle of the needle were purely *attractive*, it is evident that no such recession could take place. Supposing, then, that we were simply acquainted with the fact, that the end *f* of the needle is attracted by the terrestrial pole, and that we were wholly ignorant of the action of the said pole upon the end *h*, the experiment here described *would lead us infallibly to the conclusion that the end h must be repelled*. For if it were attracted, or even if it were neither attracted nor repelled, the motion of the bar must be *towards* the pole *N* instead of in the opposite direction.

Let us apply this reasoning to the experiment with the bismuth prisms already described. The motion of the magnetic needle in the case referred to is not more inexplicable, on the assumption of a purely attractive force, than is the motion of our rectangular box on the assumption of a purely repulsive one; and if the above experiment would lead to the conclusion that the end *h* of the magnetic needle is repelled, the experiment with the bismuth leads equally to the conclusion that the end *f* of the prism *hf*, fig. 2, must be *attracted* by the pole *N*. *The assumption of such an attraction, or in other words, of diamagnetic polarity, is alone capable of*

explaining the effect, and the explanation which it offers is perfect.

On the hypothesis of diamagnetic polarity, the prism *hf* turns a hostile end *h* to the magnetic pole *N*, and a friendly pole *f* away from it. Let the repulsive force acting upon the former be ϕ , and the attractive force acting upon the latter ϕ' . It is manifest that if ϕ were equal to ϕ' , as in the case of the earth's action, or in other words, if the field of force were perfectly uniform, then, owing to the greater distance of ϕ' from the axis of rotation, from the moment at which the rectangular box quits the equatorial position, which is one of unstable equilibrium, to the moment when its position is axial, the box would be incessantly drawn towards the position last referred to.

But it will be retorted that the field of force is not uniform, and that the end *h*, on account of its greater proximity to the magnet, is more forcibly repelled than the end *f* is attracted: to this I would reply, that it is only in 'fields' which are approximately uniform that the effects can be produced; but to produce motion towards the pole, it is not necessary that the field should be perfectly uniform: setting, as before, the distance of the direction of the force ϕ from the axis of rotation = d , and that of the force $\phi' = d'$, a motion towards the pole *N* will always occur whenever

$$\frac{d'}{d} > \frac{\phi}{\phi'}$$

To ascertain the diminution of the force on receding from a polar surface such as that here used, I suspended a prism of bismuth, similar to those contained in the rectangular box, at a distance of 0.9 of an inch from the surface of the pole. Here, under the action of the magnet excited by a current of ten cells, the number of oscilla-

tions accomplished in a second was 17; at 0·7 of an inch distant the number was 18; at 0·5 of an inch distant the number was 19; at 0·3 distant the number was 19·5; and at 0·2 distant the number was 20. The forces at these respective distances being so very little different from each other, it follows that a very slight deviation of the box from the equatorial position is sufficient to give the moment of ϕ' a preponderance over that of ϕ , and consequently to produce the exact effect observed in the experiment.

The consistency of this reasoning is still further shown when we operate in a field of force which diminishes speedily in intensity as we recede from the magnet. Such a field is the space immediately in front of pointed poles. Suspending our rectangular box between the points, and causing the latter to approach until the box has barely room to swing between them, it is impossible to produce the phenomena which we have just described. The intensity with which the nearest points of the bismuth bar are repelled so much exceeds the attraction of the more distant end, that the moment of attraction is not able to cope successfully with the moment of repulsion; the bars are consequently repelled *en masse*, and the length of the box takes up a position at right angles to the line which unites the poles.

It is manifest, however, that by increasing the distance between the bismuth bar and the points acting upon it, we diminish the difference of action upon the two ends of the bar. When the distance is sufficient, we can produce, with the pointed poles, all the phenomena exhibited between flat or rounded ones.

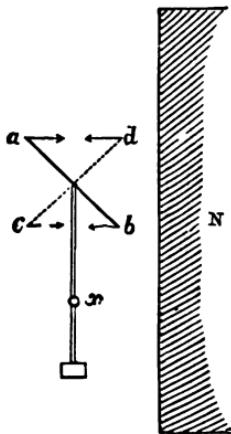
All the effects which have been described are produced with great distinctness when, instead of compressed bismuth, two similar bars of the crystallised substance are used, in which the planes of principal cleavage are parallel

to the length. Such bars are not difficult to procure, and they ought to hang in the magnetic field with the planes of cleavage vertical. It is unnecessary to describe the experiments made with such bars; they exhibit with promptness and decision all the effects observed with the compressed bismuth.

We have hitherto operated upon elongated masses of bismuth; but with the compressed substance, or with the substance crystallised uniformly in planes, as in the case last referred to, an elongation of the mass is not necessary to the production of the effects described. Previous, however, to the demonstration of this proposition, I shall introduce a kind of lemma, which will prepare the way for the complete proof.

Diamagnetic bodies, like paramagnetic ones, vary considerably in the intensity of their forces. Bismuth or antimony, for example, exhibits the diamagnetic force with

FIG. 4.



greater energy than gold or silver, just as iron or nickel exhibits the magnetic force with greater energy than platinum or chromium. Let two thin bars, *ab*, *cd*, fig. 4, of two bodies of different diamagnetic powers be placed at right angles to each other, so as to form a cross; let the cross be attached to the end of a lever and suspended horizontally from the point *x*, before the flat or rounded pole *N* of a magnet. Let the continuous line *ab* represent the needle of the powerful diamagnetic body, and the broken line *cd* that of

the feeble one. On the former a mechanical couple acts in the directions denoted by the arrows at its ends; and on the latter a couple operates in the directions of the arrows

at *its* ends. These two couples are evidently opposed to each other ; but the former being, by hypothesis, the more powerful of the two, it will overcome the latter. The mechanical advantage possessed by the *attracted* end *a* of the more powerful bar, on account of its greater distance from the axis of suspension *x*, will, in an approximately uniform field of force which we here assume, cause the centre of gravity of the cross to move towards the pole *N*.

In the formation of such a cross, however, it is not necessary to resort to two different substances in order to find two needles of different diamagnetic powers ; for in crystallised bodies, or in bodies subjected to mechanical pressure, the diamagnetic force acts with very different energies in different directions. Let a diamagnetic body which has been forcibly compressed in one direction be imagined ; let two needles be taken from such a mass, the one with its length parallel, and the other with its length perpendicular to the line of pressure. Two such needles, though composed of the same chemical substance, will behave exactly as the two bars of the cross in the experiment last described : that needle whose length coincides with the line of pressure will bear the same relation to the other that the needle of the powerfully diamagnetic substance bears to that of the feeble one. An inspection of the table at page 180 will show that this must be the case.

It is also shown in the following table, that in masses of crystallised bismuth the diamagnetic repulsion acts with very different energies in different directions. From a bismuth crystal cubes were taken with the planes of principal cleavage parallel throughout to two opposite faces of each cube. The cubes were placed upon the ends of a torsion balance, and the diamagnetic repulsion was accurately measured when the force acted parallel to the planes of cleavage. The cubes were then turned 90° round,

and the repulsion was measured when the force acted perpendicular to the planes referred to.

Cubes of crystallised Bismuth.

Strength of magnet	Repulsion when the force was directed	
	along the cleavage	across the cleavage
3·6	11·7	8
5·7	34·8	23
8·4	78	53
10·0	118	76·5
11·9	153	110

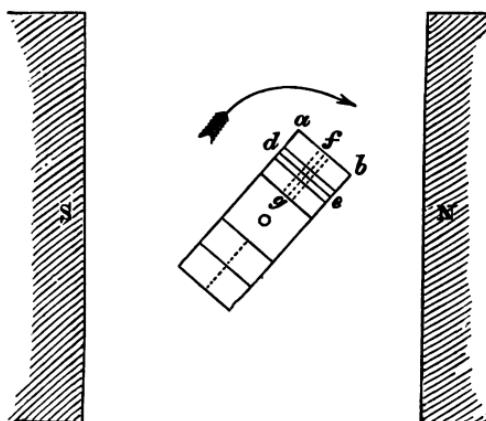
It is manifest from this table that bismuth behaves as a body of considerably superior diamagnetic power when the force acts *along* the planes of cleavage.

Let two indefinitely thin needles be taken from such a mass, the one with its length parallel, and the other with its length perpendicular to the planes of cleavage; it is evident that if two such needles be formed into a cross and subjected to experiment in the manner above described, the former will act the part of the more powerfully diamagnetic needle, and produce similar effects in the magnetic field.

We now pass on to the demonstration of the proposition, that it is not necessary that the crystallised masses should be elongated to produce the effects exhibited by the prisms in the experiments already recorded. Let us suppose the ends of our rectangular box to be composed of cubes, instead of elongated masses, of crystallised bismuth, and let the planes of principal cleavage be supposed to be parallel to the face *ab*, fig. 5. Let the continuous line *de* represent an indefinitely thin slice of the cube passing through its centre, and the dotted line *gf* a similar slice in a perpendicular direction. These two slices manifestly represent the case of the cross in fig. 4; and were they alone active, the rectangular box, in a uniform field of magnetic force, must turn in the direction of the arrow.

Comparing similar slices, *in pairs*, on each side of those two central slices, it is manifest that every pair parallel to the line *de* represents a stronger mechanical couple than every corresponding pair parallel to *fg*. The consequence

FIG. 5.



is, that a cube of crystallised bismuth suspended in the manner described, in a sufficiently uniform field of magnetic force, will move in the same direction as the cross in fig. 4: its centre of gravity will therefore *approach* the pole *N*—which was to be demonstrated.

This deduction is perfectly illustrated by experiment. It is manifest that the effect of the pole *S* upon the cube adjacent to it is to increase the moment of rotation of the rectangular box: the same reasoning applies to it as to the pole *N*.

Referring to fig. 27*a*, page 175, it will be seen that we have here dealt with the second and gravest objection of M. Matteucci, and converted the facts upon which the objection is based into a proof of diamagnetic polarity, so cogent that it alone would seem to be sufficient to decide this important question.

Holding the opinion entertained by M. Matteucci re-

garding the non-polarity of diamagnetic force,¹ his objection must have appeared to him to be absolutely unanswerable: I should be glad to believe that the remarks contained in this Appendix furnish, in the estimation of this distinguished philosopher, a satisfactory explanation of the difficulty which he has disclosed.

Let me, in conclusion, briefly direct the reader's attention to the body of evidence laid before him in the foregoing pages. It has been proved that matter is repelled by the pole of a magnet in virtue of an induced condition into which the matter is thrown by such a pole. It is shown that the condition evoked by one pole is not that which is evoked by a pole of an opposite quality—that each pole excites a condition peculiar to itself. A perfect antithesis has been shown to exist between the deportment of paramagnetic and diamagnetic bodies when acted on by a magnet alone, by an electric current alone, or by a magnet and an electric current combined. The perplexing phenomena resulting from molecular structure have been laid open, and the antithesis between paramagnetic and diamagnetic action traced throughout. It is further shown, that whatever title to polarity the deportment of a bar of soft iron, surrounded by an electric current, and acted on by other magnets, gives to this substance, a bar of bismuth possesses precisely the same title: the disposition of forces, which in the former case produces attraction, produces in the latter case repulsion, while the repulsion of the iron finds its exact complement in the attraction of the bismuth. Finally, we have a case adduced by M. Matteucci which suggests a crucial experiment to which all our previous reasoning has been submitted, by which its accuracy has been proved, and the insufficiency of the assumption, that the diamagnetic force is not polar, is reduced to demon-

¹ ‘Il ne peut exister dans les corps diamagnétiques une polarité telle qu'on la conçoit dans le fer doux.’—*Cours spécial*, p. 201.

stration. When we remember that against all this no single experimental fact¹ or theoretic argument which can in any degree be considered as conclusive, has ever been brought forward, nor do I believe can be brought forward, the conclusion seems irresistible, that we have in the agency by which bodies are repelled from the poles of a magnet, a force of the same dual character as that by which bodies are attracted; that, in short, ‘diamagnetic bodies possess a polarity the same in kind but the opposite in direction to that possessed by magnetic ones.’

[The experiments and reasonings recorded in the foregoing memoir left no shadow of doubt upon my mind as to the polar character of the diamagnetic force. Throughout the most complex series of actions, the doubleness of action to which the term polarity has been applied, was manifested in a clear and conclusive manner. Still I thought it would contribute to the final settlement of the question if I were to take up the subject after the method of Weber, and satisfy all the demands which had been made upon him by the opponents of diamagnetic polarity. Here, as in the foregoing enquiry, it was my wish to render the experiments exhaustive, and to employ apparatus which should place it definitely within the power of all investigators to subject the question to experimental demonstration. I devised a scheme of experiment, but, previous to putting it into execution, wrote to Prof. Weber asking him whether he did not think it possible so to improve his apparatus as materially to exalt the action. Weber’s own experiments had been made with bismuth solely. It was objected that his results were due to ordinary induced currents, and he was called upon to produce the same

¹ I refrain from alluding to the negative results obtained by Mr. Faraday in repeating M. Weber’s experiments; for though admirably suited to the exhibition of certain effects of ordinary induction, Mr. Faraday himself has shown how unsuitable the apparatus employed would be for the investigation of the question of diamagnetic polarity. See Experimental Researches (2653, 2654), vol. iii. p. 143.—J. T., May 9, 1855.

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effects with insulators. This demand it was my object to meet, and I think it has been met by the experiments recorded in the 'Fifth Memoir.'¹—J. T., 1870.]

¹ Professor Weber's practical reply to my question is given at page 198.

FIFTH MEMOIR.

*FURTHER RESEARCHES ON THE POLARITY OF
THE DIAMAGNETIC FORCE.¹**Introduction.*

A YEAR ago I placed before the Royal Society the results of an investigation ‘On the Nature of the Force by which Bodies are repelled from the Poles of a Magnet.’² The simultaneous exhibition of attraction and repulsion in the case of magnetised iron or steel is the basis on which the idea of the polarity of this substance is founded; and it resulted from the investigation referred to, that a corresponding duality of action was manifested by bismuth. In those experiments the bismuth was the moveable object upon which fixed magnets were caused to act, and from the deflection of the bismuth its polarity was inferred. But, inasmuch as such action is reciprocal, we ought also to obtain evidence of diamagnetic polarity by reversing the conditions of experiment—making the magnet the moveable object, and inferring from its deflection the polarity of the mass which produces the deflection. This experiment would be complementary to those described in the communication just referred to, and existing circumstances invested

¹ From the Philosophical Transactions for 1856, part i.; having been received by the Royal Society November 27, 1855, and read December 20, 1855.

² Philosophical Transactions, 1855; and Phil. Mag. for September 1855.

the question with a great degree of interest and importance.

In fact, an experiment similar to that here indicated was made by Professor W. Weber, previous to my investigation, and the result was such as to satisfy its author of the reverse polarity of diamagnetic bodies. I will not here enter into a minute description of the instrument and mode of experiment by which this result was obtained ; for the instrument made use of in the present enquiry being simply a refinement of that employed by Weber, its explanation will embrace the explanation of his apparatus. For the general comprehension of the criticisms to which Weber's results have been subjected, it is necessary, however, to remark, that in his experiments a bismuth bar, within a vertical spiral of copper wire, through which an electric current was transmitted, was caused to act upon a steel magnet freely suspended outside the spiral. When the two ends of the bar of bismuth were permitted to act successively upon the suspended magnet, a motion of the latter was observed, which indicated that the bismuth bar was polar, and that its polarity was the reverse of that of iron.

Notwithstanding the acknowledged eminence of Weber as an experimenter, this result failed to produce general conviction. In his paper 'On the Polar or other Condition of Diamagnetic Bodies,'¹ Faraday had shown that results quite similar to those obtained by Weber, in his first investigation with bismuth, were obtained in a greatly exalted degree with gold, silver, and copper; the effect being one of induced currents and not of diamagnetic polarity. He by no means asserted that his results had the same origin as those obtained by Weber ; but as the latter philosopher had made no mention of the source

¹ Experimental Researches, 2640, Philosophical Transactions, 1850, p. 171.

of error which Faraday's experiments rendered manifest, it was natural to suppose that it had been overlooked, and the observed action attributed to a wrong cause. In an article published in his 'Massbestimmungen' in 1852, Weber, however, with reference to this point, writes as follows:—'I will remark that the article transferred from the Reports of the Society of Sciences of Saxony to Poggendorff's *Annalen* was only a preliminary notice of my investigation, the special discussion of which was reserved for a subsequent communication. It will be sufficient to state here, that in the experiments referred to I sought to eliminate the inductive action by suitable combinations; but it is certainly far better to set aside this action altogether, as has been done in the experiments described in the present memoir.'

One conviction grew and strengthened throughout these discussions—this, namely, that in experiments on diamagnetic polarity great caution is required to separate the pure effects of diamagnetism from those of ordinary induced currents. With reference to even the most recent experiments of Weber, referred to at the conclusion of the citation just made, it is strongly urged that there is no assurance that the separation referred to has been effected. In those experiments, as already stated, a cylinder of bismuth was suspended within a long vertical helix of covered copper wire, and the action of the cylinder upon a magnet *suspended opposite to the centre or neutral point of the helix* was observed. To increase the action, the position of the cylinder was changed at each termination of the minute swing of the magnet, the amplitude of the oscillations being thus increased, and the effect rendered more sensible to the eye. Now, it is urged, there is every reason to believe that in these motions of a metallic mass within an excited helix induced currents will be developed, which, acting upon the magnet, will

produce the motions observed. The failure indeed to demonstrate the existence of diamagnetic polarity by other means has, in the case of some investigators, converted this belief into a certainty.

Among the number whom Weber's experiments have failed to convince, Matteucci occupies a prominent place. With reference to the question before us, this philosopher writes as follows :—¹

'In reading the description of the experiments of M. Weber, we are struck on beholding the effects produced by moving the bismuth when there is no current in the spiral. Although the direction of oscillation in this latter case is opposed to that observed when the spiral is active, still the fact excites doubts as to the correctness of the conclusions which have been drawn from these experiments.² To deduce rigorously the demonstration of diamagnetic polarity, it would be necessary to substitute for the massive bismuth, cylinders formed of insulated particles of the metal,³ to vary the dimensions of the cylinder, and above all, to compare the effects thus obtained with those which would probably be obtained with cylinders of copper and silver in a state of purity.'

'We are obliged,' continues Matteucci, 'to make the same remarks on another series of experiments executed by this physicist with a view to obtain anew, by the effects

¹ *Cours spécial sur l'Induction*, p. 206.

² It is not my place to account for the effect here referred to. I may, however, remark, that there appears to be no difficulty in referring it to the ordinary action of a diamagnetic body upon a magnet. It is the result which Brugmans published upwards of half a century ago; the peculiar form of this result in one of the series of experiments quoted by M. Weber must, I think, be regarded as purely accidental.—J. T.

³ Also in page 204 :—'Il fallait donc, pour prouver si l'influence d'un corps diamagnétique produit sur un aimant une variation de sens contraire à celle développée dans le fer doux, opérer avec ce corps *privé de conductibilité*'.

of induction, the proof of diamagnetic polarity. It is astonishing, that after having sought to neutralise the development of induced currents in the moving cylinders of bismuth, by means of a very ingenious disposition of the spiral—it is astonishing, I repeat, that no attempt was made to prove by preliminary essays with metals possessing a higher conductivity than bismuth, that the same end could be obtained. I cannot leave you [Matteucci is here addressing his pupils] ignorant that the doubts which I have ventured to advance against the experiments of M. Weber are supported by the negative result which I have obtained in endeavouring to excite diamagnetic polarity in bismuth by the discharge of the Leyden jar.'

It will be seen in the following pages that the conditions laid down by Matteucci for the rigorous demonstration of diamagnetic polarity are more than fulfilled.

The conclusions of Weber find a still more strenuous opponent in his countryman Professor v. Feilitzsch, who has repeated Weber's experiments, obtained his results, but who denies the validity of his inferences. M. v. Feilitzsch argues, that in the experiments referred to it is impossible to shut out ordinary induction, and for the rigorous proof of diamagnetic polarity he demands that the following conditions shall be fulfilled.¹ 'To render the experiment free from the action of induced currents two ways are open. The currents can be so guided that they shall mutually neutralise each other's action upon the magnet, or the induced currents can be *completely got rid of* by using, instead of a diamagnetic conductor, a diamagnetic insulator.' To test the question, M. v. Feilitzsch resorted to the latter method: instead of cylinders of bismuth he made use of cylinders of wax, and also employed a prism of heavy glass, but in neither case was he able to detect

¹ Poggendorff's *Annalen*, xcii. 377.

the slightest action upon the magnet. ‘However the motions of the prism might be varied, it was not possible either to cause the motionless magnet to oscillate, or to bring the magnet from a state of oscillation to one of rest.’ M. v. Feilitzsch pushes his experiments further, and finds that when the bismuth is *motionless* within its spiral, the position of the magnet is just the same as when the bismuth is entirely withdrawn; hence his final conclusion, that the deflection of the magnet in Weber’s experiments is due to induced currents, which are excited in the bismuth by its mechanical motion up and down within the spiral.

These divergent opinions upon a question of such vital bearing upon the general theory of magnetic phenomena, naturally excited in me the desire to make myself acquainted with the exact value of Weber’s experiments. The most direct way of accomplishing this I considered to be, to operate with an instrument similar to that made use of by Weber himself; I therefore resolved to write to the constructor of his apparatus, but previous to doing so I wrote to M. Weber, enquiring whether his further reflections on the subject had suggested to him any desirable modification of his instrument. In reply to my question he undertook to devise for me an apparatus, surpassing in delicacy any hitherto made use of. The design of M. Weber was ably carried out by M. Leyser of Leipzig; and with the instrument thus placed in my possession, I have been able to satisfy the severest conditions proposed by those who saw in the results of Weber’s experiments the effects of ordinary induction.

Description of Apparatus.

A sketch of the instrument employed in the present investigation is given in fig. 2. B O, B’O’ is the outline of a rectangular box, the front of which is removed so as

to show the apparatus within. The back of the box is prolonged, and terminates in two semicircular projections, which have apertures at H and H' . Stout bolts of brass, which have been made fast in solid masonry, pass through these apertures, and the instrument, being secured to the bolts by screws and washers, is supported in a vertical position, being free from all disturbance save such as affects the foundations of the Royal Institution. All the arrangements presented to the eye in fig. 2 are made fast to the back of the box, but are unconnected with the front, so as to permit of the removal of the latter. $\text{w w}'$ are two boxwood wheels with grooved peripheries, which permit of motion being transferred from one wheel to the other by means of a string ss' . Attached to this string are two cylinders, mn , op , of the body to be examined: in some cases the cylinders are perforated longitudinally, the string passing through the perforation, and the cylinders being supported by knots on the string. H E , $\text{H}'\text{E}'$ are two helices of copper wire overspun with silk, and wound round two brass reels, the upper ends of which protrude from H to g , and from H' to g' . The internal diameter of each helix is 0.8 of an inch, and its external diameter about 1.3 inch; the length from H to g is 19 inches, and the centres of the helices are 4 inches apart; the diameters of the wheels $\text{w w}'$ being also 4 inches. The cross bar $\text{g g}'$ is of brass, and through its centre passes the screw R . From this screw depend a number of silk fibres which support an astatic arrangement of two magnets, the front one of which, s n , is shown in the figure. An enlarged horizontal section of the instrument through the astatic system is shown in fig. 4. The magnets are connected by a brass cross-piece, in which is the point of suspension P , fig. 4; and the position of the helices is shown to be between the magnets. It will be seen that the astatic system is a horizontal one, and not vertical, as in the ordinary galvanometer. The black

circle in front of the magnet s n , fig. 2, is a mirror, which is shown in section at m , fig. 4; to balance the

FIG. 1.

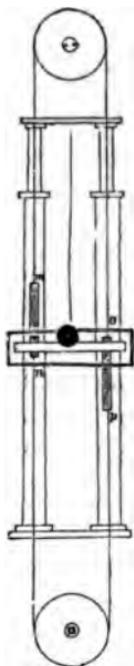


FIG. 2.

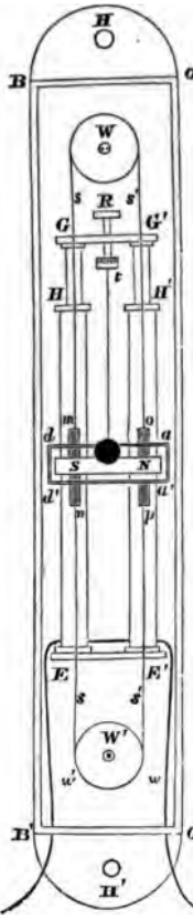


FIG. 3.

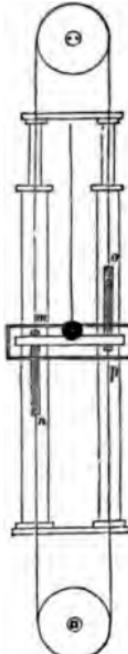
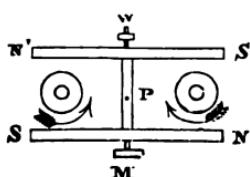


FIG. 4.



weight of this mirror, and adjust the magnets in a horizontal position, a brass washer, w , is caused to move along a screw, until a point is attained at which its weight brings both the magnets into the same horizontal plane.

There is also another adjustment, which permits of the magnets being brought closer together or separated more widely asunder.

The motions of this compound magnet are observed by means of a distant scale and telescope, according to the method applied to the magnetometer of Gauss. The rectangle da , $d'a'$, fig. 2, is the section of a copper damper, which, owing to the electric currents induced in it by the motion of the magnet, brings the latter rapidly to rest, and thus expedites experiment.

It is well known that one end of a magnet attracts, while the other end repels the same pole of a magnetic needle; and that between the two poles there is a neutral point which neither attracts nor repels. The same is the case with the helices $H E$, $H'E'$; so that when a current is sent through them, if the astatic magnet be exactly opposite the neutral point, it is unaffected by the helices. This is scarcely attainable in practice; a slight residual action remains which draws the magnets against the helices; but this is very easily neutralised by disposing an external portion of the circuit so as to act upon the magnets in a direction opposed to that of the residual action. Here then we have a pair of spirals which, when excited, do not act upon the magnets, and which therefore permit us to examine the pure action of any body, capable of magnetic excitement, placed within them.

In the experiments to be described, it was arranged that the current should always flow in opposite directions through the two spirals; so that if the cylinders within them were polar, the two upper ends of these cylinders should be poles of opposite names, and consequently the two lower ends also opposite. Suppose the two cylinders mn , op to occupy the central position indicated in fig. 2: then, even if the cylinders became polar through the action of the surrounding current, the astatic magnets,

being opposite to the neutral points of the cylinders, would experience no action from the latter. But suppose the wheel w' to be so turned that the two cylinders are brought into the position shown in fig. 1, the upper end o of op and the lower end n of mn will act simultaneously upon the suspended magnets. For the sake of illustration, let us suppose the ends o and n to be both north poles, and that the section, fig. 4, is taken when the bars are in the position shown in fig. 1. The right-hand pole o will attract s' and repel n , which attraction and repulsion will sum themselves together to produce a deflection of the system of magnets. On the other hand, the left-hand pole n , being also north, will attract s and repel n' , which two effects also sum themselves to produce a deflection in the same direction as the former two. Hence, not only is the action of terrestrial magnetism annulled by this arrangement, but the moving force, due to the reciprocal action of the magnets and the bodies within the helices, is increased fourfold. By turning the wheel in the other direction, we bring the cylinders into the position shown in fig. 3, and thus may study the action of the ends m and p upon the magnets.

The screw r is employed to raise or lower the magnets. At the end, t , of the screw is a small torsion circle which can be turned independently; by means of the latter the suspending fibre can be twisted or untwisted without altering the level of the magnets.

The front is attached to the box by brass hasps, and opposite to the mirror M a small plate of glass is introduced, through which the mirror is observed; the magnets within the box being thus effectually protected from the disturbances of the external air. A small handle to turn the wheel w' accompanied the instrument from its maker; but in the experiments, I used, instead of it, a key attached to the end of a rod 10 feet long; with this rod in my right

hand, and the telescope and scale before me, the experiments were completely under my own control. Finally, the course of the current through the helices was as follows:—Proceeding from the platinum pole of the battery it entered the box along the wire w , fig. 2, which passed through the bottom of the box; thence through the helix to H' , returning to E' ; thence to the second helix, returning to E , from which it passed along the wire w' to the zinc pole of the battery. A commutator was introduced in the circuit, so that the direction of the current could be varied at pleasure.

Experiments.—Department of Diamagnetic Bodies.

A pair of cylinders of chemically pure bismuth, 3 inches long and 0·7 of an inch in diameter, accompanied the instrument from Germany. These were first tested, commencing with a battery of one cell of Grove. Matters being as sketched in fig. 2, when the current circulated in the helices and the magnet had come to rest, the cross wire of the telescope cut the number 482 on the scale. Turning the wheel w' so as to bring the cylinders into the position fig. 1, the magnet moved promptly, and after some oscillations took up a new position of equilibrium; the cross wire of the telescope then cut the figure 468 on the scale. Reversing the motion so as to place the cylinders again central, the former position 482 was resumed; and on turning further in the same direction, so as to place the cylinders as in fig. 3, the position of equilibrium of the magnet was at the number 493. Hence by bringing the two ends n and o to bear upon the astatic magnet, the motion was from greater to smaller numbers, the position of rest being then fourteen divisions less than when the bars were central. By bringing the ends m and p to bear upon the magnet, the motion was from smaller to greater

numbers, the position of rest being eleven divisions more than when the bars were central.

As the positions here referred to will be the subject of frequent reference, for the sake of convenience I will call the position of the cylinders sketched in fig. 1, Position 1 ; that sketched in fig. 2, Position 2 ; and that sketched in fig. 3, Position 3. The results which we have just described, tabulated with reference to these terms, would then stand thus :—

I.

Bismuth Cylinders.—Length 3 inches ; diameter 0.7.		
Position 1. 468	Position 2. 482	Position 3. 493

In changing therefore from position 1 to position 3, a deflection corresponding to twenty-five divisions of the scale was produced.

Wishing to place myself beyond the possibility of illusion as regards the fact of deflection, I repeated the experiment with successive batteries of two, three, and four cells. The following are the results :—

II.

	2 cells	3 cells	4 cells
Position 1.	450	439	425
Position 2.	462	450	437
Position 3.	473	462	448

In all the cases cited we observe the same result. From position 2 to position 1 the motion is from larger to smaller numbers ; while from position 2 to position 3 the motion is from smaller to larger numbers.

It may at first sight appear strange that the amount of the deflection did not increase with the battery power ; the reason, in part, is that the magnet, when the current circulated, was held in a position free from the spirals, by forces emanating partly from the latter and partly from a portion of the external circuit. When the current increased, the magnetisation of the bismuth increased also, but so did

the force which held the magnets in their position of equilibrium. To remove them from this position, a greater amount of force was necessary than when only the residual action of a feeble current held them there. This fact, coupled with the circumstance that less heat was developed, and less disturbance caused by air currents, when a feeble battery was used, induced me for some time to experiment with a battery of two cells. Subsequent experience however enabled me to change this for five cells with advantage.

Notwithstanding the improbability of the argument, it may still be urged that these experiments do not prove beyond a doubt that the bismuth cylinders produce the observed motion of the magnets, in virtue of their excitement by the voltaic current; for it is not certain that these cylinders would not produce the same motion wholly independent of the current. Something of this kind has already occurred to M. Leyser,¹ and why not to others?

In answer to this, I reply, that if the case be as here suggested, the motion of the magnets will not be changed when the current in the helices flows in the opposite direction. Here is the experiment.

III.

Position 1. 670

Position 2. 742

Position 3. 704

We observe here that in passing from position 2 to position 1 the motion is from smaller to larger numbers; while in passing from position 2 to position 3 the motion is from larger to smaller numbers. This is the opposite result to that obtained when the current flowed in the opposite direction; and it proves that *the polarity of the bismuth cylinders depends upon the direction of the surrounding current, changing as the latter changes.* It was pleasant

¹ Scientific Memoirs, New Series, vol. i. page 184.

to observe the prompt and steady march of the magnet as the cylinders were shifted in the helices. When the magnets, operated on by two ends of the bars of bismuth, were moving in any direction, by bringing the two opposite ends into action, the motion could be promptly checked ; the magnets could be brought to rest, or their movement converted into one in the opposite direction.

I may add to the above a series of results obtained some days subsequently in the presence of Professors Faraday, De la Rive, and Marcer.

IV.

Bismuth Cylinders.

Position 1. 670	Position 2. 650	Position 3. 630
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The difference between positions 1 and 3 amounts here to forty divisions of the scale ; subsequent experience enabled me to make it still greater.

It was found by experiment, that when the motion was from lower to higher numbers it denoted that the poles $N N'$, fig. 4, were repelled from the spirals, and the poles $s s'$ attracted towards them. When, on the contrary, the motion was from larger to smaller numbers, it indicated that the poles $N N'$ were attracted and the poles $s s'$ repelled. In the position fig. 1, therefore, of Tables III. and IV. the poles $N N'$ were repelled by the ends $n' o$ of the bismuth cylinders, and the poles $s s'$ attracted ; while in the position fig. 3, the poles $N N'$ were attracted by the ends $m p$, and the poles $s s'$ repelled ; the ends n and o , therefore, acted as two north poles, while the ends m and p acted as two south poles. Now the direction of the current in the experiments recorded in the two tables referred to was that shown by the arrows in fig. 4. Standing in front of the instrument, the direction in the adjacent face of the spiral $n'E'$ was from right to left, while it was

from left to right in H.E. Hence, the polarity of the bismuth cylinders was the reverse of that which would be excited in cylinders of iron under the same circumstances. This assertion, however, shall be transferred, before we conclude, from the domain of deduction to that of fact.

Let us now urge against these experiments all that ever has been urged against the experiments of Weber by the opponents of diamagnetic polarity. The bismuth cylinders are metallic conductors, and, in moving them through the spirals, induced currents will be excited in these conductors. The motion observed may not, after all, be due to diamagnetic polarity, but to the currents thus excited. I reply, that in all cases the number set down marks the *permanent* position of the magnet. Were the action due to induced currents, these, being momentary, could only impart a *shock* to the magnet, which, on the disappearance of the currents, would return to its original position. But the deflection is permanent, and is therefore due to an enduring cause. In his paper on 'Supposed Diamagnetic Polarity,' Faraday rightly observes:—'If the polarity exists, it must be in the particles, and for the time permanent, and therefore distinguishable from the momentary polarity of the mass due to induced temporary currents, and it must also be distinguishable from ordinary magnetic polarity by its contrary direction.' These are the precise characteristics of the force made manifest by the experiments now under consideration.

Further, the strength of induced currents depends on the conducting power for electricity of the mass in which they are formed. Expressing the conducting power of bismuth by the number 1.8, that of copper would be expressed by 73.6,¹ the conductivity of the latter being therefore forty times that of the former. Hence arises the demand, made by the opponents of diamagnetic polarity,

¹ Philosophical Magazine, Series 4, vol. vii. p. 37.

to have the experiments repeated with cylinders of copper ; for if the effect be due to induced currents, they will show themselves in copper in a greatly increased degree. The following is the result of a series of experiments made with two copper cylinders, of the same dimensions as the bismuth ones already described :—

V.

Cylinders of Copper.

Position 1. 754	Position 2. 754	Position 3. 755
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If the effects obtained with bismuth were due to induced currents, we ought to have the same effects forty times multiplied in the case of copper, in place of which we have scarcely any sensible effect at all.

Bismuth is the only substance which has hitherto produced an appreciable action in experiments of this nature ; another illustration, however, is furnished by the metal antimony, which possesses a greater conductive power, but a less diamagnetic power than bismuth. The following results were obtained with this substance :—

VI.

Cylinders of Antimony.—Length 3 inches; diameter 0·7.

	Current direct ¹	Current reversed ²
Position 1. 693	244	
Position 2. 688	252	
Position 3. 683	261	

On comparing these numbers with those already obtained with bismuth, we observe that for like positions the actions of both metals are alike in direction. We further observe that the results are determined, not by the relative *conducting* powers of the two metals, but by their relative *diamagnetic* powers. If the former were the determining cause, we should have greater deflections with antimony than with bismuth, which is not the case ; if the latter, we should have less deflections, which is the case.

¹ As in III. and IV.

² As in I. and II.

The third and severest condition proposed by those who object to the experiments of Weber is to substitute insulators for conductors. I call this condition severe for the following reasons:—according to the experiments of Faraday,¹ when bismuth and sulphur are submitted to the same magnetising force, the repulsion of the former being expressed by the number 1968, that of the latter is expressed by 118. Hence an action which, with the means hitherto employed by Faraday and others, was difficult of detection in the case of bismuth, must wholly escape such means of observation in the case of sulphur. The same remarks apply, in a great measure, to all other insulators.

But the admirable apparatus made use of in this investigation has enabled me to satisfy this condition also. To Faraday I am indebted for the loan of two prisms of the self-same heavy glass with which he made the discovery of diamagnetism. The bismuth cylinders were withdrawn from the helices and the prisms of glass put in their places. It was now necessary to have a perfectly steady magnet, the expected result being so small as to be readily masked by, or confounded with, a motion arising from some extraneous disturbance. The feeble warmth developed in the helices by an electric current from two cells was found able to create air currents of sufficient power to defeat all attempts to obtain the pure action of the prisms. To break up these air currents I stuffed all unfilled spaces of the box with old newspapers, and found the expedient to answer perfectly. With a fresh battery, which delivered a constant current throughout the duration of an experiment, the magnet was admirably steady,² and under these favourable conditions the following results were obtained:—

¹ Phil. Mag. March 1853, p. 222.

² It was necessary, however, to select a portion of the day when Albemarle Street was free from cabs and carriages, as the shaking of

VII.

Prisms of Heavy Glass.—Length 3 inches; width 0·6; depth 0·5.

Current direct	Current direct	Current direct
Position 1. 664	Position 2. 662	Position 3. 660

Thus in passing from position 1 to 3, or *vice versa*, a permanent deflection corresponding to four divisions of the scale was produced. By raising or lowering the respective prisms at the proper moments the amplitude of the oscillations could be considerably augmented, and, when at a maximum, could be speedily extinguished by reversing the motions of the prisms. In six different series of experiments made with this substance the same invariable result was obtained. It will be observed that the deflections are, in all cases, identical in direction with those produced by bismuth under the same circumstances.

The following results were afterwards obtained with the same prisms in the presence of M. de la Rive; the current was 'direct.'

VIII.

Position 1. 652	Position 2. 650	Position 3. 648
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On the negative result arrived at with this substance, it will be remembered that Von Feilitzsch bases one of his arguments against the conclusions of Weber.

Calcareous spar was next submitted to experiment. Two cylinders of the transparent crystal were prepared and examined in the manner already described. The results are as follows:—

IX.

Cylinders of Calcareous Spar.—Length 3 inches; diameter 0·7.

Current direct	Current direct	Current direct
Position 1. 699·5	Position 2. 698·5	Position 3. 697·5

Here, as in the other cases, the deflection was permanent, and the entire building, by the rolling of these vehicles, rendered the magnets unsteady.

could be augmented by the suitable raising or lowering of the respective cylinders. The action is small, but perfectly certain. The magnet was steady and moved promptly and invariably in the directions indicated by the numbers. It will be observed that the deflections are the same in kind as those produced by bismuth.

The intrusion of other employments compelled me to postpone the continuation of these experiments for several weeks. On taking up the subject again, my first care was to assure myself that the instrument retained its sensibility. Subsequent to the experiments last recorded it had been transported over several hundred miles of railway, and hence the possibility of a disturbance of its power. The following experiments, while they corroborate the former ones, show that the instrument retained its power and delicacy unimpaired :—

X.

Bismuth Cylinders.

	Current direct	Current reversed
Position 1.	612	264
Position 2.	572	230
Position 3.	526	200

The deflections, it will be observed, are the same in kind as before ; but by improved manipulation the effect is augmented. In passing from position 1 to 3 we have here a deflection amounting in one case to 64, and in the other to 86 divisions of the scale.

To Mr. Noble I am indebted for two cylinders of pure statuary marble ; the examination of these gave the following results :—

XI.

Cylinders of Statuary Marble.—Length 4 inches ; diameter 0·7.

	Current direct	Current reversed
Position 1.	601	215
Position 2.	598	218
Position 3.	596	220

Here, in passing from position 1 to 3, we have a permanent deflection corresponding to five divisions of the scale. As in all other cases, the impulsion of the magnet might be augmented by changing the position of the cylinders at the limit of each swing. The deflections are the same in kind as those produced by bismuth, which ought to be the case, for marble is diamagnetic.

An upright iron stove influenced by the earth's magnetism becomes a magnet, with its bottom a north and its top a south pole. Doubtless, though in an immensely feebler degree, every erect marble statue is a true diamagnet, with its head a north pole and its feet a south pole. The same is certainly true of a man as he stands upon the earth's surface, for all the tissues of the human body are diamagnetic.

A pair of cylinders of phosphorus enclosed in thin glass tubes were next examined.

XII.

Cylinders of Phosphorus.—Length 3·5 inches; diameter 0·63.

	Current direct	Current reversed
	Series I.	Series II.
Position 1.	620	670
Position 2.	618	668
Position 3.	616	666
		224
		226
		228

The change of the bars from position 1 to 3 is in this case accompanied by permanent deflection corresponding to four divisions of the scale. The deflection and polarity is that of a diamagnetic body. The magnet was remarkably steady during these experiments, and the consequent clearness and sharpness of the result pleasant to observe.

XIII.

Cylinders of Sulphur.—Length 6 inches; diameter 0·7.

	Current direct	Current reversed
Position 1.	658·5	222
Position 2.	657	223·5
Position 3.	655·5	225·5

XIV.

Cylinders of Nitre.—Length 3·5 inches; diameter 0·7.

	Current direct	Current reversed
Position 1.	648·5	263
Position 3.	647	265

Finally, as regards solid diamagnetic bodies, a series of experiments was made with wax; this also being one of the substances whose negative deportment is urged by Von Feilitzsch against Weber.

XV.

Cylinders of Wax.—Length 4 inches; diameter 0·7.

	Current direct	Current reversed
Position 1.	624·5	240
Position 3.	623	241

The action is very small, but it is nevertheless perfectly certain, and proves the polarity of the wax. The argument founded on the negative deportment of this substance must therefore give way. When we consider the feebleness of the action with so delicate a means of examination, the failure of Von Feilitzsch to obtain the effect, with an instrument constructed by himself, will not excite surprise.

Thus, in the case of seven insulating bodies, the existence of diamagnetic polarity has been proved. The list might be augmented without difficulty; but sufficient I trust has been done to remove the scruples of those who saw in Weber's results an action produced by induced currents.

Polarity of Diamagnetic Liquids.

A portion of the subject hitherto untouched by experimenters, but one of great interest, has reference to the polar condition of liquids while under magnetic influence.

The first liquid examined was distilled water; it was enclosed in thin glass tubes, corked at the ends; and by

means of a loop passing round the cork, the tubes were attached to the string passing round the wheels *ww*. Previous to use, the corks were carefully cleansed, so that any impurity contracted in cutting, or by contact with ferruginous matters, was completely removed. The following are the results obtained with this liquid :—

XVI.

Cylinders of Distilled Water.—Length 4 inches ; diameter 0·65.

	Current direct	Current reversed
Position 1.	605	246
Position 2.	603	248
Position 3.	601	250

The experiment was many times repeated, but always with the same result ; indeed, the polarity of the water is as safely established as that of iron. Pure water is diamagnetic, and the deflections produced by it are the same as those of all the other diamagnetic bodies submitted to examination.

From the position which it occupies in Faraday's list,¹ I had also some hopes of proving the polarity of sulphide of carbon. The following results were obtained :—

XVII.

Cylinders of Bisulphide of Carbon.—Length 4 inches ; diameter 0·65.

	Current direct	Current reversed
Position 1.	631	210
Position 2.	629	213
Position 3.	626	216

As in the case of distilled water, we observe a deflection in one direction when the current is 'direct,' and in the other when it is 'reversed,' the action in the first case, in passing from position 1 to 3, amounting to five, and in the latter case to six divisions of the scale. The polarity of the substance is therefore established, and it is that of diamagnetic bodies.

¹ Phil. Mag. March 1853, p. 222.

Department of Magnetic Bodies.

Thus far we have confined our examination to diamagnetic substances : turn we now to the deportment of magnetic bodies when submitted to the same conditions of experiment. Here we must select substances suitable for examination, for all are not so. Cylinders of iron, for example, of the same size as our diamagnetic cylinders, would, through the intensity of their action, quite derange the apparatus ; so that we are obliged to have recourse to bodies of smaller size or of feebler magnetic capacity. Besides, the remarks of writers on this subject render it of importance to examine, whether bodies through which the magnetic constituents are very sparingly distributed present a veritable polarity the same as that exhibited by iron itself.

Slate rock usually contains from eight to ten per cent. of oxide of iron, and a fragment of the substance presented to the single pole of an electro-magnet is attracted by the pole. A cylinder of slate from the Penrhyn quarries near Bangor was first examined. It was not found necessary to increase the effect by using two cylinders, and the single one used was suspended in the right-hand helix H'E'. The deportment of the substance was as follows :—

XVIII.

Cylinder of Penrhyn Slate.—Length 4 inches ; diameter 0·7.

	Current direct	Current reversed
Position 1.	620	280
Position 2.	647	240
Position 3.	667	198

Comparing these deflections with those obtained with diamagnetic bodies, we see that they are in the opposite direction. With the direct current a change from position 1 to 3 is followed, in the case of diamagnetic bodies, by a

motion from higher to lower numbers; while in the present instance the motion is from lower numbers to higher. In the former case the north poles of the astatic magnet are attracted, in the latter they are repelled. We also see that a *direct* current acting on diamagnetic bodies produces the same deflection as a *reverse* current on magnetic ones. Thus, as promised at page 207, the opposite polarities of diamagnetic and magnetic bodies are transferred from the region of deduction to that of fact.

XIX.

Cylinder of Caermarthen Slate.—Length 4 inches; diameter 0·7.

	Current direct	Current reversed
Position 1.	664	300
Position 2.	690	235
Position 3.	720	185

The deflections in this case are also indicative of magnetic polarity.

These two cylinders were so taken from the rock that the axis of each lay in the plane of cleavage. The following experiments, made with a cylinder of the same size, show the capability of a rock of this structure to be magnetised across the planes of cleavage.

XX.

Cylinder of Slate: axis of cylinder perpendicular to cleavage.

	Current direct	Current reversed
Position 1.	655	240
Position 2.	678	205
Position 3.	695	192

Chloride of iron was next examined: the substance, in powder, was enclosed in a single glass tube, which was attached to the string passing round the wheels w w' of the instrument.

XXI.

Cylinder of powdered Chloride of Iron.—Length 3·8 inches diameter 0·5.

	Current direct	Current reversed
Position 1.	185	990
Position 2.	—	230
Position 3.	990	185

The deflection here indicates magnetic polarity. The action was very powerful. When swiftly moving in any direction, a change in the position of the cylinder instantly checked the magnet in its course, brought it to rest, or drove it forcibly in the opposite direction. The numbers 185 and 990 mark indeed the utmost limit between which it was possible for the magnet to move; here it rested against the helices.

Two glass tubes were filled with red oxide of iron and examined. The action of the poles of these cylinders upon the magnets was so strong, as to efface, by the velocity imparted to the magnets, all distinct impression of the numbers on the scale. By changing the position of the tubes within the helices, the magnets could be driven violently through the field of view, or could be held rigidly against the respective helices. As in all other cases, the centres of the cylinders were neutral points, and the two ends of each were poles of opposite qualities. The polarity was the same as that of iron.

A small quantity of iron filings was kneaded thoroughly in wax, and a cylinder formed from the mass. Its deportment was also very violent, and its polarity was just as clear and pronounced as that of a solid cylinder of iron could possibly be.

Sulphate of iron was next examined: the crystallised substance was enclosed in two glass tubes and tested in the usual manner.

XXII.

Cylinders of Sulphate of Iron.—Length 4·5 inches; diameter 0·7.

	Current direct	Current reversed
Position 1.	510	510
Position 2.	600	370
Position 3.	700	220

The red ferroprussiate of potassa is a magnetic salt; with this substance the following results were obtained:—

XXIII.

Cylinders of red Ferroprussiate of Potassa.—Length 4·5 inches; diameter 0·65.

	Current direct	Current reversed
Position 1.	610	250
Position 2.	630	220
Position 3.	655	197

In this case also the crystallised salt was enclosed in glass tubes.

Two glass tubes were next filled with carbonate of iron in powder; the following are the results:—

XXIV.

Cylinders of Carbonate of Iron.—Length 4 inches; diameter 0·5.

Current direct	Current direct	Current direct
Position 1. 185	Position 2. 620	Position 3. 740

In all these cases the deflections show that the cylinders of powder are true magnets, being polar after the manner of iron.

Polarity of Magnetic Liquids.

As the complement of the experiments made with diamagnetic liquids, we now pass on to the examination of the polarity of magnetic liquids. A concentrated solution of sulphate of iron was enclosed in two glass tubes and submitted to examination.

XXV.

Sulphate of Iron Solution in tubes.—Length 4 inches; diameter 0·65.

Current direct	Current direct	Current direct
Position 1. 548	Position 2. 600	Position 3. 648

A solution of muriate of nickel, examined in the same manner, gave the following results :—

XXVI.

Muriate of Nickel Solution in tubes.—Length 3·6 inches ; diameter 0·65.

	Current direct	Current reversed
Position 1.	605	224
Position 2.	632	200
Position 3.	650	185

A solution of muriate of cobalt yielded as follows :—

XXVII.

Muriate of Cobalt solution in tubes.—Length 3·6 inches ; diameter 0·65.

	Current direct	Current reversed
Position 1.	630	262
Position 2.	645	235
Position 3.	660	202

In all these cases we have ample evidence of a polar action the reverse of that exhibited by diamagnetic liquids. These are the first experiments in which the action of either liquid magnets, or liquid diamagnets, upon a suspended steel magnet has been exhibited.

Thus far then the following substances have been submitted to examination :—

Diamagnetic bodies	Magnetic bodies
Bismuth.	Penrhyn slate.
Antimony.	Slate, axis parallel to cleavage.
Heavy glass.	Slate, axis perpendicular to cleavage.
Calcareous spar.	Chloride of iron.
Statuary marble.	Sulphate of iron.
Phosphorus.	Carbonate of iron.
Sulphur.	Ferrocyanide of potassium.
Nitre.	Oxide of iron.
Wax.	Iron filings.
Liquids	Liquids
Distilled water.	Sulphate of iron.
Bisulphide of carbon.	Muriate of nickel.
	Muriate of cobalt.

Every substance in each of these lists has been proved to be polar under magnetic influence, the polarity of the diamagnetic bodies being invariably opposed to that of the magnetic ones.

In his investigation on the supposed polarity of diamagnetic bodies, Faraday made use of a core of sixpenny pieces, and obtained with it the results he sought. Wishing to add the testimony of silver as a good conductor to that of copper, two cylinders were formed of sixpenny pieces, covered with paper, and submitted to experiment. The following are the results obtained :—

XXVIII.

Silver Cylinders (sixpenny pieces).

Current direct	Current direct	Current direct
Position 1. 724	Position 2. 774	Position 3. 804

The action here was prompt and energetic, strongly contrasted with the neutrality of copper; but the deflection was permanent, and could not therefore be the result of induced currents. Further, it was a deflection which showed magnetic polarity, whereas pure silver is feebly diamagnetic. The cylinders were removed and examined between the poles of an electro-magnet; they proved to be magnetic.

On observing this deportment of the silver, I tried the copper cylinders once more. The results with a direct current were,—

XXIX.

Position 1. 766	Position 2. 767	Position 3. 768
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Here almost the same neutrality as before is evidenced.

Deeming that the magnetism of the cores of silver coins was due to magnetic impurity attaching itself to the paper which covered them, a number of fourpenny pieces were procured, washed in ammonia and water, and enclosed in thin glass tubes. The following were the results :—

XXX.

Silver Cylinders (fourpenny pieces).

Current direct	Current direct	Current direct
Position 1. 490	Position 2. 565	Position 3. 660

Here also we have a very considerable action indicative of magnetic polarity. On examining the cylinders between the poles of an electro-magnet, they were found decidedly magnetic. This, therefore, appears to be the common character of our silver coins. [They doubtless contain a trace of iron.] The tubes which contained the pieces were sensibly neutral.

Knowing the difficulty of demonstrating the existence of diamagnetic polarity in ordinary insulators, Matteucci suggested that insulated fragments of bismuth ought to be employed, the insulation being effected by a coat of lac or resin. I constructed a pair of cylinders in accordance with the suggestion of M. Matteucci. The following are the results they yielded with a direct current:—

XXXI.

Position 1. 730	Position 2. 750	Position 3. 768
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Here we have a very marked action, but the polarity indicated is magnetic polarity. On subsequent examination, the cylinders proved to be magnetic. This was due to impurities attaching themselves to the resin.

But the resin may be done away with and the powdered metal still rendered an insulator. This thought was suggested to me by an experiment of Faraday, which I will here describe. Referring to certain effects obtained in his investigations on supposed diamagnetic polarity, he writes thus:—"If the effect were produced by induced currents in the mass, division of the mass would stop these currents and so alter the effect; whereas, if produced by a *true diamagnetic polarity*, division of the mass would not affect the polarity seriously or in its

essential nature. Some copper filings were therefore digested for a few days in dilute sulphuric acid to remove any adhering iron, then well washed and dried, and afterwards warmed and stirred in the air, until it was seen by the orange colour that a very thin film of oxide had formed upon them; they were finally introduced into a glass tube and employed as a core. It produced no effect whatever, but was as inactive as bismuth.' (Exper. Resear. 2658.)

Now when bismuth is powdered and exposed to the action of the air, it very soon becomes tarnished, even without heating. A quantity of such powder was prepared, and its conducting power for electricity tested. The clean ends of two copper wires proceeding from a battery of Grove were immersed in the powder; but though the wires were brought as near as possible to each other, short of contact, not the slightest action was observed upon a galvanometer placed in the circuit. When the wires touched, the needle of the galvanometer flew violently aside, thus proving that the current was ready, but that the powder was unable to conduct it. Two glass tubes were filled with the powder and submitted to experiment. The following results were obtained:—

XXXII.

Cylinders of Bismuth Powder.

Length 3 inches.	Diameter 0·7.	
	Current direct	Current reversed
Position 1.	640	230
Position 2.	625	245
Position 3.	596	260

These deflections are the same in kind as those obtained with the cylinders of massive bismuth. We have here no cessation of action. *The division of the mass does not affect the result seriously or in its essential nature, and hence the deportment exhibits the characteristics of 'a true diamagnetic polarity.'*

In summing up the results of his enquiry on this subject, Mr. Faraday writes thus:—‘Finally, I am obliged to say that I can find no experimental evidence to support the hypothetical view of diamagnetic polarity, either in my own experiments, or in the repetition of those of Weber, Reich, and others. . . . It appears to me also, that, as magnetic polarity conferred by iron or nickel in small quantity, and in unfavourable states, is far more easily indicated by its effects upon an astatic needle, or by pointing between the poles of a strong horseshoe magnet, than by any such arrangement as mine or Weber's or Reich's, so *diamagnetic polarity would be much more easily distinguished in the same way.*’ I was struck, on reading this passage, to find how accurately the surmise has been fulfilled by the instrument with which the foregoing experiments were made. In illustration of the powers of this instrument, as compared with that made use of by Mr. Faraday, I may be permitted to quote the following result from his paper on supposed diamagnetic polarity so often referred to:—‘A thin glass tube, $5\frac{1}{2}$ inches by three-quarters of an inch, was filled with a saturated solution of proto-sulphate of iron, and employed as an experimental core; the velocity given to the machine at this and all average times was such as to cause five or six approaches and withdrawals of the core in one second; yet the solution produced no sensible indication on the galvanometer.’ Referring to Table XXV., it will be seen that the instrument made use of in the present enquiry has given with a solution of protosulphate of iron a deflection amounting to no less than one hundred divisions of the scale. Mr. Faraday proceeds:—‘A tube filled with small crystals of protosulphate of iron caused the needle to move about 2° Red oxide of iron produced the least possible effect.’ In the experiments recorded in the foregoing pages, the crystallised

sulphate of iron gave a deflection of nearly two hundred divisions of the scale, while the red oxide gave a deflection as wide as the helices would permit, which corresponds to about eight hundred divisions of the scale. The correctness of Faraday's statement regarding the inferiority of the means first devised to investigate this subject, is thus strikingly illustrated. It might be added, that red ferroprussiate of potash and other substances, which have given me powerful effects, produced no sensible impression in experiments made with Faraday's instrument.

Thus have we seen the objections raised against diamagnetic polarity fall away one by one, and a body of evidence accumulated in its favour, which places it among the most firmly established truths of science. This I cannot help thinking is, in great part, to be attributed to the bold and sincere questioning of the principle when it seemed questionable. The cause of science is more truly served, even by the denial of what may be a truth, than by the indolent acceptance of it on insufficient grounds. Such denials drive us to a deeper communion with Nature, and, as in the present instance, compel us through severe and laborious enquiry to strive after certainty, instead of resting satisfied, as we are prone to do, with mere probable conjecture.

Royal Institution, November 1855.

SIXTH MEMOIR.

*ON THE RELATION OF DIAMAGNETIC POLARITY
TO MAGNE-CRYSTALLIC ACTION.¹*

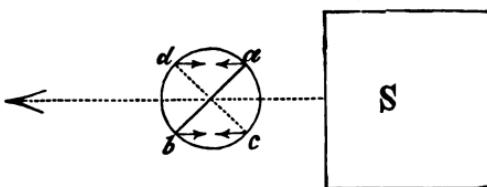
[COMPLETION OF ARGUMENT.]

In a communication presented to the Royal Society some weeks ago, the fact of diamagnetic polarity was established for a great variety of substances, including insulators, such as phosphorus, sulphur, calcareous spar, statuary marble, heavy glass, and nitre. The demonstration was also extended to distilled water and other liquids; the conditions proposed by the opponents of diamagnetic polarity for its rigorous demonstration being thereby fulfilled. The importance of the principle is demonstrated by the fruitfulness of its consequences; for by it we obtain a clear insight of effects which, without it, would remain standing enigmas in science, being connected by no known tie with the ordinary laws of mechanics. Many of the phenomena of magne-crystallic action are of this paradoxical character. For the sake of those who see no clear connection between these and the other effects of magnetism, as well as for the sake of completeness, I will here endeavour to indicate in a simple manner, and from my own point of view, the bearing of the question of polarity upon that of magne-crystallic action. I will commence with the elementary phenomena, and select for illustration, as I proceed, cases of real difficulty which have been actually encountered by those who have worked experimentally at the subject.

¹ Phil. Mag., vol. ii. p. 123.

To free our thoughts from all effects except those which are purely magne-crystallic, we will for the present operate with spheres. Let a sphere of carbonate of lime be suspended before the pole s, fig. 1, of an electro-magnet, so that the axis of the crystal shall be horizontal. Let the line *ab* mark any position of the axis inclined to the direction of the force emanating from s (marked by the large arrow); and let the dotted line *dc* make an equal angle with the direction of the force at the other side. As the sphere is diamagnetic, the face of it which is turned towards s will, according to the principles established in the foregoing memoirs, be hostile to s, while that turned from s will be friendly

FIG. 1.



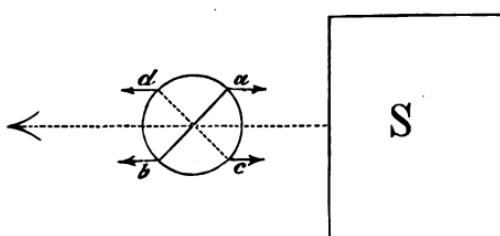
to s; and, if the sphere were homogeneous, the tendency to set *ab* at right angles to the direction of the force would be exactly neutralised by the tendency to set *cd* in the same position: the sphere would consequently stand still. But the case is otherwise when the intensity of diamagnetisation along *ab* is greater than along *cd*, which I have elsewhere proved to be the fact.¹ If, adopting a line of argument already pursued, we suppose the sphere to vanish, with the exception of two thin needles taken along the lines mentioned, the hostile pole at *a* will be stronger than that at *c*, and the friendly pole at *b* will be stronger than that at *d*; hence, the ends *a* and *b* being acted upon by a mechanical couple of superior power, the line *ab* will

¹ Phil. Mag., S. 4, vol. ii. . 176, and at p. 63 of this volume.

recede from its inclined position, and finally set itself *at right angles* to the direction of the force. Whatever be the inclination of the line *ab* to the magnetic axis, this superiority will belong to its couple; the entire sphere will therefore turn in the manner here indicated, and finally set with the axis of the crystal equatorial. This is the result established by experiment.

For the diamagnetic calcium, contained in this crystal, let the magnetic element, iron, be substituted. Each molecule of the crystal becomes thereby magnetic; we have carbonate of iron in place of carbonate of lime; and the axis which, in the latter substance, is that of maximum

FIG. 2.



repulsion, is that of maximum attraction in the former. This, I think, is one of the most suggestive points¹ that researches in magne-crystalline action have hitherto established, namely, that the same arrangement of molecules influences the paramagnetic and diamagnetic forces in the same way, intensifying both in the same direction. Let us suppose, then, that the sphere of carbonate of iron is suspended as in fig. 2, the line *ab* being the axis of the crystal. I have already shown this line to be that in which the magnetic induction is most intense.² Comparing, as before, the lines *ab* and *cd*, the friendly pole *a* is stronger than *c*, and the hostile pole *b* is stronger than *d*;

¹ For its bearing upon the question of a magnetic medium see Phil. Mag., vol. ix. p. 208, and further on in this volume.

² Phil. Mag. S. 4, vol. ii. p. 177 and at p. 65 of this volume.

a residual ‘couple’ therefore acts upon *ab* in the direction indicated by the arrows, which must finally set this line *parallel* to the direction of the lines of force. This is also the result which experiment exhibits.

We will now apply the principle of polarity to some of the more complicated forms of magne-crystallic action. Some highly paradoxical effects were adduced by Faraday, in proof of the assertion that the magne-crystallic force is neither attraction nor repulsion. I cannot bring the subject in a fairer manner before the reader than by quoting Faraday’s own description of the phenomena referred to. Here it follows:—

‘Another very striking series of proofs that the effect is not due to attraction or repulsion was obtained in the following manner:—A skein of fifteen filaments of cocoon silk, about 14 inches long, was made fast above; and then a weight of an ounce or more hung to the lower end; the middle of this skein was about the middle of the magnetic field of the electro-magnet, and the square weight below rested against the side of a block of wood so as to give a steady silken vertical axis without swing or revolution. A small strip of card, about half an inch long and the tenth of an inch broad, was fastened across the middle of this axis by cement; and then a small prismatic crystal of sulphate of iron 0·3 of an inch long and 0·1 in thickness, was attached to the card, so that the length and also the magne-crystallic axis were in the horizontal plane; all the length was on one side of the silken axis, so that as the crystal swung round, the length was radius to the circle described, and the magne-crystallic axis parallel to the tangent.

‘When the crystal was made to stand between the flat-faced poles, the moment the magnet was excited it moved, tending to stand with its length equatorial, or its magne-crystallic axis parallel to the lines of force. When

one pole was removed and the experiment repeated, the same effect took place, but not so strongly as before ; finally, when the pole was brought as near to the crystal as it could be without touching it, the same result occurred, and with more strength than in the last case. In the two latter experiments, therefore, the crystal of sulphate of iron, though a magnetic body, and strongly attracted by such a magnet as that used, actually *receded* from the pole of the magnet under the influence of the magne-crystallic condition.

'If the pole s be removed, and that marked n be retained¹ for action on the crystal, then the latter approaches the pole urged by both the magnetic and magne-crystallic forces ; but if the crystal be revolved 90° to the left, or 180° to the right, round the silken axis, so as to come into the contrary or opposite position, then this pole repels or rather causes the removal to a distance of the crystal, just as the former did. The experiment requires care, and I find that conical poles are not good ; but with attention I could obtain the results with the utmost readiness.

'The sulphate of iron was then replaced by a crystalline plate of bismuth, placed, as before, on one side of the silk suspender, and with its magne-crystallic axis horizontal.² Making the position the same as that which the crystal had in relation to the n pole in the former experiment, so that to place its axis parallel to the lines of magnetic force it must approach this magnetic pole, and then throwing the magnet into an active state, the bismuth

¹ The figures will be given and explained further on.

² It will be borne in mind that Faraday calls the line in a crystal which sets from pole to pole, the magne-crystallic axis of the crystal, whether the latter is paramagnetic or diamagnetic. In bodies of the former class, however, the 'axis' sets from pole to pole because the attraction along it is a maximum ; while in bodies of the latter class, the 'axis' sets from pole to pole because the repulsion along the line perpendicular to it is a maximum.

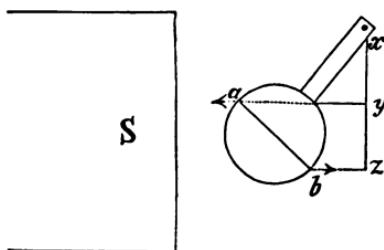
moved accordingly and did approach the pole, against its diamagnetic tendency, but under the influence of the magne-crystallic force.

'Hence a proof that neither attraction nor repulsion governs the set. This force, then, is distinct in its character and effects from the magnetic and diamagnetic forms of force.'

These experiments present grave difficulties, and, without invoking the aid of diamagnetic polarity, they are inexplicable. That principle once established, they follow from it as the simplest mechanical consequences. I will now endeavour to apply the idea of a force which is *both* attractive *and* repulsive, or in other words of a *polar* force, to the solution of these difficulties.

For the sake, once more, of disencumbering the mind of all considerations save those which belong to pure magne-crystallic action, we will suppose the bodies experimented with to be spherical.

FIG. 3.

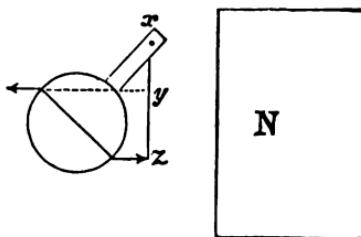


Let the dot at x , fig. 3, be the intersection of the vertical silken axis with Faraday's strip of card; and on the end of the strip, let the sphere of sulphate of iron be placed with its magne-crystallic axis ab at right angles to the length of the strip. This line, as I have already shown,¹ is that of most intense magnetisation through the

¹ Phil. Mag., S. 4, vol. ii. p. 178, and at p. 66 of this volume.

crystal. The forces acting on the sphere in its present position are exactly similar to those acting upon the carbonate of iron in fig. 2. A residual 'couple' will apply itself at the extremities of ab , as indicated by the arrows, and would, if the sphere were free to turn round its centre of gravity, set the line ab parallel to the lines of force. But the sphere is here rigidly connected with a lever moveable round its own axis of suspension, and it is easy to state the mechanical result that must follow from this arrangement. To obtain the 'moments' of the two forces acting upon a and b , we have to multiply each of them by the distance of its point of application from the axis x . Now in front of a flat pole such as that made use of by Faraday in these experiments, the force diminishes very slowly as we recede from the pole. The consequence is that the attraction of a does not so far exceed the repulsion of b as to prevent the product of the latter into zz from exceeding that of the former into xy , and consequently the paramagnetic sphere must recede from the pole.¹ Faraday's result is thus explained.

FIG. 4.



In his next experiment, Faraday removed the pole s and allowed the pole N to act upon the crystal as in fig. 4. In this case it will be seen that the end nearest

¹ [Calling the attraction a , the force with which the sphere tends to turn *towards* the magnet is equal to $a \times xy$. Calling the repulsion r , the force with which the sphere tends to retreat from the magnet is $r \times zz$. If a be not much greater than r , the product $r \times zz$ will exceed $a \times xy$, and the sphere, *though magnetic*, must retreat as if repelled by the pole.]

the pole, and therefore the most strongly attracted, is also at the greatest distance from the axis of rotation. Hence the sphere must approach the pole, as in Faraday's experiment.

When the strip of card is revolved 90° , we have the state of things shown in fig. 5; and when it is revolved 180° , we have the state of things shown in fig. 6. It is

FIG. 5.

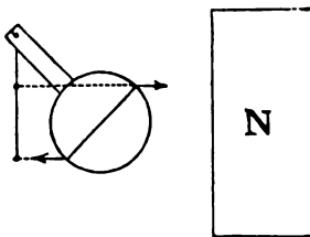
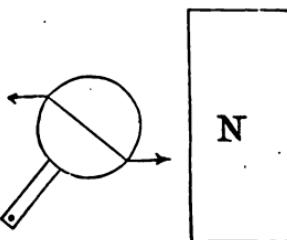


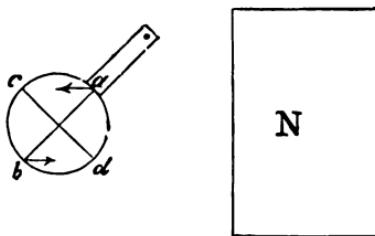
FIG. 6.



manifest, for the mechanical reasons already assigned, that the crystal, in both these cases, must recede from the pole. Faraday's difficulty thus disappears.

Substituting for the sphere of sulphate of iron a sphere of bismuth with its magne-crystallic axis cd , fig. 7, per-

FIG. 7.



pendicular to the strip of card, the bismuth is found by Faraday to approach the pole when the magnet is excited. The line ab , perpendicular to that called the magne-crystallic axis, has been shown by Faraday himself to be that

of greatest diamagnetic intensity ; the mass is therefore under the influence of forces precisely similar to those acting on the carbonate of lime in fig. 1. A ‘residual couple,’ as denoted by the arrows, will act at the extremities of the line *ab*. The absolute repulsion of *a* in the field of force here assumed, does not differ much from the absolute attraction of *b* ; but the latter force acts at the end of a much longer lever, and consequently the sphere is drawn towards the excited pole. I cannot help remarking here upon the severe faithfulness with which these results are recorded, and on the inestimable value of such records to scientific progress. The key to their solution being once found, the investigator may proceed confidently to the application of his principles, without fear of check or perplexity arising from the imperfection of his data.

In all these cases we have assumed that the magnetic force *diminishes slowly as we recede from the pole*. This is essential to the production of the effects. The exact expression of the condition is, *that the advantage due to the proximity of the part of the mass nearest the pole, must be less than that arising from the greater leverage possessed by the force acting on the more distant parts*. When the shape of the poles is such that the diminution of the force with the increase of distance is too speedy for the above condition to be fulfilled, the phenomena no longer exhibit themselves. It is plain that the diminution of the force as we recede from a pointed pole must be more rapid than when we recede from a magnetised surface, and hence it is that Faraday finds that ‘conical poles are not good.’ It is also essential that the length of the lever which supports the magne-crystallic body shall bear a sensible ratio to the distance between the two points of application of the magnetic force. If the lever be long, *recession* will take place in cases where, with a shorter lever, *approach* would be observed.

It is well known that a piece of soft iron is attracted most strongly by the angles and corners of a magnet, and hence it is sometimes inferred that the magnetic force emanating from these edges and corners is more intense than that issuing from the central parts of the polar surfaces. Such experiments, however, when narrowly criticised, do not justify the inference drawn from them. They simply show that the *difference* between attraction and repulsion, on which the final attraction depends, is greater at the edges than elsewhere; but they do not enable us to infer the absolute strength of either the attraction or the repulsion, or, in other words, of the force of magnetisation. The fact really is, that *while the attraction of the mass is nearly absent in the central portion of a magnetic field bounded by two flat poles, the magnetisation is really stronger there than between the edges.* This is proved by the following experiment:—

I suspended a cube of crystallised bismuth from a fibre of cocoon silk; when the magnet was excited, the cube set its planes of principal cleavage equatorial. When drawn aside from this position and liberated, it oscillated to and fro through it. Between the upper edges of the moveable poles the number of oscillations performed in a minute was seventy-six; in the centre of the field the number performed was eighty-eight, and between the lower edges eighty. A cube of magnetic slate, similarly suspended, oscillated in the centre of the field forty-nine times, and between the edges only forty times, in fifteen seconds. In the former position there was no sensible tendency of the cube to move towards either pole; but in the latter position, though the magnetisation was considerably less intense, the cube was with difficulty prevented from moving up to one or the other of the edges. The reason of all this manifestly is, that while the forces in the centre of the field nearly neutralise each other as regards the

translation of the mass, they are effective in producing its *oscillation*; while between the edges, though the absolute forces acting on the north and south poles of the excited substances are less intense, the *difference* of these forces, owing to the speedier diminution of the force with the distance, is greater than in the centre of the field. It is therefore an error to infer, that, because the *attraction* of the mass is greater at the edges and corners than in the centre of the field, the *magnetising force* of the former must therefore be more intense than that of the latter.¹

There is another interesting and delicate experiment of Faraday's to which I am anxious to apply the principle of diamagnetic polarity: the experiment was made with a view of proving that 'the magne-crystallic force is a force acting at a distance.' 'The crystal,' writes Faraday, 'is moved by the magnet at a distance, and the crystal can also move the magnet at a distance. To produce the latter result, I converted a steel bodkin, 3 inches long, into a magnet, and then suspended it vertically by a cocoon filament from a small horizontal rod, which again was suspended by its centre and another length of cocoon filament, from a fixed point of support. In this manner the bodkin was free to move on its own axis, and could also describe a circle about 1½ inch in diameter; and the latter motion was not hindered by any tendency of the needle to point under the earth's influence, because it could take any position in the circle and yet remain parallel to itself.'

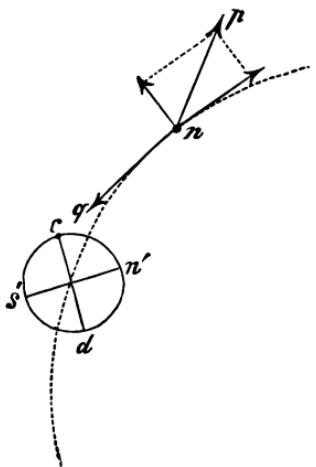
'When a crystal of bismuth was fixed on a support with the magne-crystallic axis in a horizontal direction, it could be placed near the lower pole of the magnet in any position; and being then left for two or three hours, or until by repeated examination the magnetic pole was found to be stationary, the place of the latter could be examined,

¹ Some important consequences resulting from this experiment are intended for a future communication.

and the degree and direction in which it was affected by the bismuth ascertained. . . . The effect produced was small; but the result was, that if the direction of the magne-crystallic axis made an angle of 10° , 20° , or 30° with the line from the magnetic pole to the middle of the bismuth crystal, then the pole followed it, tending to bring the two lines into parallelism; and this it did whichever end of the magne-crystallic axis was towards the pole, or whichever side it was inclined to. By moving the bismuth at successive times, the deviation of the magnetic pole could be carried up to 60° . The crystal, therefore, is able to react upon the magnet at a distance. But though it thus takes up the character of a force acting at a distance, still it is due to that power of the particles which makes them cohere in regular order, and gives the mass its crystalline aggregation; which we call at other times the attraction of aggregation, and so often speak of as acting at insensible distances.'

The disposition of this important experiment will be manifest from fig. 8, where cd is the magne-crystallic axis

FIG. 8.



of a sphere of bismuth, or the line in which the diamagnetic induction is least intense; and $s'n'$ the direction of the principal cleavage, or that of most intense diamagnetisation. Let n be the point of the bodkin, say its north pole, the crystal will be excited by the influence of this pole, and the resultant action will be the same as if it were exclusively 'diamagnetised' along the line $s'n'$. At the end nearest to the pole of the bodkin a repelled pole n' will be excited in the bismuth; at the

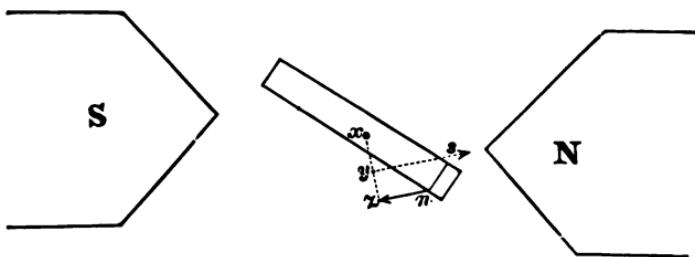
most distant end an attracted pole s' will be excited. Let the repulsive force tending to separate n from n' be represented by the line np and let the attraction exerted between s' and n be represented by the line nq ; the arrangement is such that the force of s' acts more nearly in the direction of the tangent than that of n' ; the latter may be decomposed into two, one acting along the circle and the other across it: the latter component exerts a pressure against the axis of suspension; the former only is effective in causing the pole n to move; so that the whole, or nearly the whole, of the attraction has to compete with a comparatively small component of the repulsion. The former therefore preponderates, and the pole n approaches the crystal. It is manifest that as the angle which the line from n to the centre of the crystal makes with the magne-crystallic axis, increases, the component of repulsion which acts in the direction of a tangent to the curve, augments also; and that at a certain point this component must become preponderant. Beyond an angle of 30° it is to be presumed that Mr. Faraday did not obtain the effect. Removing the crystal, and placing a small magnet in the position of the line $s' n'$, with its poles arranged as in the figure, the same phenomena would be produced.¹

As finally illustrative of the sufficiency of the principle of polarity to explain the most complicated phenomena of magne-crystallic action, let us turn to the consideration of those curious effects of rotation first observed by M. Plücker, and illustrated by thirty-seven cases brought forward in the Bakerian Lecture for 1855. The effects, it will be remembered, consisted of the turning of elongated paramagnetic bodies suspended between *pointed poles* from the axial to the equatorial position, and of elongated

¹ As there are no measurements given of the distances between the crystal and the pole, it is of course impossible to do more than indicate generally the theoretic solution of the experiment.

diamagnetic bodies, from the equatorial to the axial position, when the distance between the suspended body and the poles was augmented. This is a subject of considerable difficulty to many, and I therefore claim the indulgence of those who have paid more than ordinary attention to it, if in this explanation I should appear to presume too far on the reader's want of acquaintance with the question. Let us then suppose an elongated crystal of tourmaline, staurolite, ferrocyanide of potassium, or beryl, *cr*, to be suspended between the conical poles *N*, *S*, fig. 9, of an electro-magnet; supposing the position between the poles to be the oblique one shown in the figure, let us inquire what are the forces acting upon the crystal

FIG. 9.



in this position. In the case of all paramagnetic crystals which exhibit the phenomenon of rotation, it will be borne in mind that the line of most intense magnetisation is at right angles to the length of the crystal. Let *sn* be any transverse line near the end of the crystal; fixing our attention for the present on the action of the pole *N*, we find that a friendly pole is excited at *s* and a hostile pole at *n*: let us suppose *s* and *n* to be the points of application of the polar force, and, for the sake of simplicity, let us assume the distance from the point of the pole *N* to *s* to be half of the distance from *N* to *n*. We will further suppose the action of the pole to be that of a magnetic point, to which, in reality, it approximates; then, inas-

much as the quantities of north and south magnetism are equal, we have simply to apply the law of inverse squares to find the difference between the two forces. Calling that acting on s unity, that acting on n will be $\frac{1}{4}$. Opposed to this difference of the absolute forces is the difference of their moments of rotation ; the force acting on n is applied at a greater distance from the axis of rotation, but it is manifest that to counterbalance the advantage enjoyed by s , on account of its greater proximity, the distance $x z$ would require to be four times that of $x y$. Taking the figure as the correct sketch-plan of the poles and crystal, it is plain that this condition is not fulfilled, and that hence the end of the crystal will be drawn towards

FIG. 10.



the pole N . What we have said of the pole N is equally applicable to the pole s , so that such a crystal suspended between two such poles, in the manner here indicated, will set its length along the line which unites them.

While the crystal retains the position which it occupied in fig. 9, let the poles be removed further apart, say to ten times their former distance. The ratio of the two forces acting on the two points of application s and n will be now as the square of 11 to the square of 10, or as 6 : 5 nearly. Taking fig. 10, as in the former case, to be the exact sketch of the crystal, it is manifest that the ratio of $x z$ to $x y$ is greater than that of 6 to 5,¹ the advantage,

¹ At a distance, moreover, the whole mass of the pole, not its point alone, comes into play.

on account of greater leverage, possessed by the force acting on n is therefore greater than that which greater proximity gives to s , and the consequence is that the crystal will recede from the pole, and its position of rest between two poles placed at this distance apart will be at right angles to the line which joins them. It is needless for me to go over the reasoning in the case of a diamagnetic body whose line of strongest diamagnetisation is perpendicular to its length. Reversing the direction of the arrows in the last two figures, we should have the graphic representation of the forces acting upon such a body; and a precisely analogous mode of reasoning would lead us to the conclusion, that when the polar points are near the crystal, the latter will be driven towards the equatorial position, while where they are distant, the crystal will be drawn into the axial position. In this way the law of action laid down empirically in the Bakerian Lecture for 1855 is deduced *a priori* from the polar character of both the magnetic and diamagnetic forces. The most complicated effects of magne-crystallic action are thus reduced to mechanical problems of extreme simplicity; and, inasmuch as these actions are perfectly inexplicable except on the assumption of diamagnetic polarity, they add their evidence in favour of this polarity to that already furnished in such abundance.

Perhaps as remarkable an illustration as could be chosen of the apparently perplexing character of certain magnetic phenomena, but of their real simplicity when the exact nature of the force producing them is understood, is furnished by the following experiment. I took a quantity of pure bismuth powder and squeezed it between two clean copper plates until the powder became a compact mass. A fragment of the mass suspended before the pointed pole of a magnet was forcibly repelled; and when suspended in the magnetic field with the direction of pressure horizontal, in accordance with results already

sufficiently well known, it set its line of pressure equatorial.

A second quantity of the bismuth powder was taken, and with it was mixed powdered carbonate of iron, amounting to $\frac{3}{10}$ ths per cent. of the whole; the mass was still strongly diamagnetic, but the line of compression, instead of setting equatorial as in the former instance, set decidedly axial.

A portion of the mixed powder was next taken, in which the magnetic constituent amounted to 1 per cent. The mass was still diamagnetic, but the line of compression set axial; it did so when the influence of exterior form was quite neutralised, so that the effect must be referred solely to the compression of the mass. With 2 per cent. of carbonate of iron powder the mass was magnetic, and set, with increased energy, its line of compression axial; with 4 per cent. of carbonate of iron the same effect was produced in a still more exalted degree.

Now, why should the addition of a quantity of carbonate of iron powder, which is altogether insufficient to convert the mass from a diamagnetic into a paramagnetic one, be able to overturn the tendency of the diamagnetic body to set its line of compression equatorial? The question is puzzling at first sight, but the difficulty vanishes on reflection. The repulsion of the bismuth, when suspended before a pointed pole, depends upon its general capacity for diamagnetic induction, while its position as a magnecrystal between flat poles depends on the difference between its capacities in two different directions. The diamagnetic capacity of the substance may be very great while its capacity in different directions may be nearly alike, or quite so: the former, in the case before us, came into play before the pointed pole; but between the flat poles, where the *directive*, and not the *translative* energy is great, the carbonate of iron powder, whose directive

power, when compressed, far exceeds that of bismuth, determined the position of the body. In this simple way a number of perplexing results obtained with bodies formed of a mixture of paramagnetic and diamagnetic constituents, may be shown capable of satisfactory explanation.

Finally, inasmuch as the set of the mass in the magnetic field depends upon the difference of its excitement in different directions, it follows that any circumstance which affects all directions of a magne-crystallic mass in the same degree will not disturb the differential action upon which its deportment depends. This seems to me to be the explanation of the results recently obtained by Mr. Faraday with such remarkable uniformity, namely, that, no matter what the medium may be in which the magne-crystallic body is immersed, whether air or liquid, paramagnetic or diamagnetic, it requires, in all cases, the same amount of force to turn it from the position which it takes up in virtue of its structure.¹

I have thus dwelt upon instances of magne-crystallic action which have revealed themselves in actual practice, as affording the best examples for the application of the key which the demonstration of the polarity of the diamagnetic force places in our possession; and I believe it has been shown that these phenomena, which were in the highest degree paradoxical when first announced, are deducible with perfect ease and certainty from the action of polar forces. *The whole domain of magne-crystallic action is thus transferred from a region of mechanical enigmas to one in which our knowledge is as clear and sure as it is regarding the most elementary phenomena of magnetic action.*

¹ I need hardly draw attention to the suggestive beauty of this experiment.—J. T., 1870.

1. LETTER FROM PROFESSOR W. WEBER.

The honoured name of Prof. Wilhelm Weber has been mentioned more than once in the foregoing Memoirs. To him I forwarded a copy of the Bakerian Lecture for 1855, giving, at the same time, a sketch of some experiments which I had then executed with the instrument already referred to as designed for me by himself. He favoured me, in reply, with the following interesting communication :—

Göttingen, September 25, 1855.

‘ MY DEAR SIR,—Accept my best thanks for your kind communication of September 3 ; I am gratified to learn that the apparatus executed by M. Leyser in Leipzig for the demonstration of diamagnetic polarity has so completely fulfilled your expectations. This intelligence is all the more agreeable to me, inasmuch as before the apparatus was sent away, it was not in my power to go to Leipzig and test the instrument myself.

‘ It gave me great pleasure to learn that Mr. Faraday and M. De la Rive have had an opportunity of witnessing the experiments, and of convincing themselves as to the facts of the case.

‘ It was also of peculiar interest to me to learn that you had succeeded in establishing the polarity of the self-same heavy glass with which Faraday first discovered diamagnetism. This is the best proof that these experiments do not depend upon the conductive power of bismuth for electricity.

‘I have read with great interest your memoir “On the Diamagnetic Force,” &c. contained in the “Philosophical Transactions,” vol. cxlv. It has been your care to separate the *fact* of diamagnetic polarity from the *theory*, and to place the former beyond the region of doubt. Allow me, with reference to this subject, to direct your attention to a passage at page 39 of your memoir, which you adduce as a conclusion from my theory; the passage runs as follows:—

“The magnetism of two iron particles in the line of magnetisation is increased by their reciprocal action; but, on the contrary, the diamagnetism of two bismuth particles lying in this direction is diminished by their reciprocal action.”

‘This proposition is by no means a necessary assumption of my theory, but is rather a direct consequence of diamagnetic polarity, if the facts be such as both you and I affirm them to be. What, therefore, you have adduced against the above conclusion must be regarded as an argument against diamagnetic polarity itself. The *diamagnetic reciprocal action* of the bismuth particles in the line of magnetisation is necessarily opposed to the *action of the exciting magnetic force*. The latter must be enfeebled, because the diamagnetic is opposed to the *magnetic reciprocal action* of iron particles which lie in the line of magnetisation, through which latter it is known the action of the exciting magnetic force is increased. Hence also the *modification* produced in bismuth by magnetic excitement, whatever it may be, must be weakened, because the force of excitation is diminished.

‘(I believe, however, that this argument against diamagnetic polarity may also be surmounted. The phenomenon which you have observed must be referred to other circumstances, also connected with the compression of the bismuth. For the diamagnetic reciprocal action is,

as I have shown, much too weak to produce an effect which could be compared in point of magnitude with the reciprocal action produced in the case of iron.)

‘I take this opportunity of adding a few remarks for the purpose of setting my theory of diamagnetic polarity in a more correct light.

‘My theory assumes:—1, that the fact of diamagnetic polarity is granted; 2, that in regard to magnetic phenomena, Poisson’s theory of two magnetic fluids, and Ampère’s theory of molecular currents, are equally admissible. Whoever denies the first fact, or rejects the theory of Ampère, cannot, I am ready to confess, accept my theory.

‘But supposing that you do not reject Ampère’s theory of permanent molecular currents, but are disposed to enter upon the inner connection and true significance of the theory, you will easily recognise that it is by no means *an arbitrary assumption of mine*, that in bismuth molecular currents are excited, when the exciting magnetic force is augmented or diminished; but that the excitation of such molecular currents is *a necessary conclusion from the theory of Ampère*, which conclusion Ampère himself could not make, because the laws of voltaic induction, discovered by Faraday, were unknown to him. In all cases where molecular currents *exist*, by increase or diminution of the magnetic exciting force, *molecular currents must be excited*, which either add their action to, or subtract it from, the action of those already present.

‘Finally, permit me to make a few remarks on the following words of your memoir:—

“To carry out the assumption here made, M. Weber is obliged to suppose that the molecules of diamagnetic bodies are surrounded by channels, in which the induced currents, once excited, continue to flow without resistance.”

'The assumption of channels which surround the molecules, and in which the electric fluids move without resistance, is an assumption contained in the theory of Ampère, and is by no means added by me for the purpose of explaining diamagnetic polarity. *A permanent molecular current without such a channel involves a manifest contradiction*, according to the law of Ohm.

'I may further observe, that I do not wonder that you regard a theory which is built upon the assumption of such channels, as "so extremely artificial that you imagine the general conviction of its truth cannot be very strong." In a certain sense I quite agree with you, but I only wish to convince you that this objection applies really to the theory of Ampère,¹ and only applies to mine in so far as it is built upon the former. (You may perhaps find less ground for objecting to the specialty of such an assumption, if you separate the simple fundamental conception, which recommends itself particularly by a certain analogy of the molecules to the heavenly bodies in space, from those additions which Ampère was forced to make, in order to apply the mathematical methods at his command, and to make the subject one of strict calculation. He was necessitated to reduce the case to that of *linear* currents, which necessarily demand channel-shaped bounds, if every possibility of a lateral outspreading is to be avoided.)

'To place my theory of diamagnetic polarity in a truer light, I am anxious also to convince you that this theory is by no means based upon new assumptions (hypotheses), but that it only rests upon such conclusions as may be drawn from the theory of Ampère, when the laws of voltaic induction discovered by Faraday, and the laws of electric currents by Ohm, are suitably connected with it. I affirm, that, even if Faraday had not discovered diamagnetism, by the combination of Ampère's theory with Faraday's

¹ This is quite true.—J. H.

laws of voltaic induction, and Ohm's laws of the electric current, as shown in my memoir, the said discovery might possibly have been made.

'In respect, however, to the artificiality of the theory of Ampère, I hope that mathematical methods may be found whereby the limitation before mentioned to the case of linear currents may be set aside, and with it the objection against channel-form beds. All our molecular theories are still very artificial. I, for my part, find less to object to in this respect in the theory of Ampère than in other artificialities of our molecular theories; and for this reason, that in Ampère's case the nature of the artificiality is placed clearly in view, and hence also a way opened towards its removal.'¹

'To Mr. Faraday I beg of you to present my sincerest respect.

'Believe me, dear Sir,

'Most sincerely yours,

'WILHELM WEBER.'

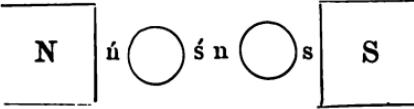
'Professor Tyndall.'

The foregoing letter possessed more than a private interest, and I therefore laid it before the readers of the 'Philosophical Magazine' for December 1855. On one point in it only did I ask permission to make a remark, and that was the proposition, that the diminution of the excitement of a row of bismuth particles in the line of magnetisation by their reciprocal action is '*a direct consequence of diamagnetic polarity.*' M. Weber (I believe)

¹ In *Heat as a Mode of Motion*, 4th edition, and elsewhere, I write thus:—'Whether we see rightly or wrongly—whether our insight be real or imaginary—it is of the utmost importance in science to aim at perfect clearness in the description of all that comes, or seems to come, within the range of the intellect. For if we are right, clearness of utterance forwards the cause of right; while if we are wrong, it ensures the speedy correction of error.' It is needless to say more to show how heartily I subscribe to the view of Professor Weber.—J. T.

found this proposition on the following considerations:— Let a series of bismuth particles lie in the axial line between the magnetic poles *n* and *s*: the polarity excited in these particles by the direct action of the poles will be

that shown in the figure,
being the reverse of that
of iron particles under the
same circumstances. But
as the end *n* of the right-



hand particle tends to excite a magnetism like its own in the end *s'* of the left-hand particle, and *vice versa*, this action is opposed to that of the magnet, and hence the magnetism of such a row of particles is enfeebled by their reciprocal action.

Now it appears to me that there is more assumed in this argument than experiment at present can bear out. There are no experimental grounds for the assumption, that what we call the north pole of a bismuth particle exerts upon a second bismuth particle precisely the same action that the north pole of an iron particle would exert. Magnetised iron repels bismuth; but whatever the *fact* may be, the *conclusion* is scarcely warranted, that *therefore* magnetised bismuth will repel bismuth. Supposing it were asserted that magnetised iron attracts iron and repels bismuth, while magnetised bismuth attracts bismuth and repels iron, would there be anything essentially impossible, self-contradictory, or absurd involved in the assertion? I think not. And yet if even the possible correctness of such an assertion be granted, the proposition above referred to becomes untenable. It will be observed that it is against a conclusion rather than a fact that I contend. With regard to the fact, I should be sorry to express a positive opinion; for this is a subject on which I am at present seeking instruction, which may lead

me either to M. Weber's view or the opposite. Be that as it may, the result cannot materially affect the respect I entertain for every opinion emanating from my distinguished correspondent on this and all other scientific subjects.

2. FARADAY ON MEDIA.

In the foregoing letter Professor Weber remarks:—‘It has been your care to separate the *fact* of diamagnetic polarity from the *theory*, and to place the former beyond the region of doubt.’ Indeed the fact was, at the time here referred to, the point in question. With regard to the theory, which lies at the root of magnetic theory generally, we have not made up our minds about it to the present hour. The *fact*, however, as we have seen, enables us to explain those numerous phenomena of magne-crystallic action which Faraday found so bewildering. With regard to theory M. E. Becquerel had, at an early stage of the controversy, regarded the phenomena of diamagnetism as illustrations of the principle of Archimedes. Bismuth, M. Becquerel assumed, was apparently repelled because of the greater attraction of the etherial medium in which it was immersed, as light wood under water is apparently repelled by the earth. Later on, Faraday made some beautiful experiments on the influence of media, and founded upon them arguments of fundamental import as regards diamagnetism. The paper from which the following is an extract will be found in the ‘Philosophical Magazine’ for February, 1855.

‘Let us now consider for a time the action of different *media*, and the evidence they give in respect of polarity. If a weak solution of protosulphate of iron,¹ *m*, be put

¹ Let *l* contain 4 grains. *m* 8 grains, *n* 16 grains, and *o* 32 grains of crystallised protosulphate of iron in each cubic inch of water.

into a selected thin glass tube about an inch long, and one-third or one-fourth of an inch in diameter, and sealed up hermetically, and be then suspended horizontally between the magnetic poles in the air, it will point axially, and behave in other respects as iron ; if, instead of air between the poles, a solution of the same kind as m , but a little stronger, n , be substituted, the solution in the tube will point equatorially, or as bismuth. A like solution somewhat weaker than m , to be called l , enclosed in a similar tube, will behave like bismuth in air but like iron in water. Now these are precisely the actions which have been attributed to polarity, and by which the assumed reversed polarities of paramagnetic and diamagnetic bodies have been considered as established ; but when examined, how will ideas of polarity apply to these cases, or they to it ? The solution l points and acts like bismuth in air and like iron in water ; are we then to conclude that it has reverse polarity in these cases ? and if so, what are the reasons and causes for such a singular contrast in that which must be considered as dependent upon its internal or molecular state ?

‘ In the first place, no want of magnetic continuity of parts can have anything to do with the inversion of the phenomena ; for it has been shown sufficiently by former experiments,¹ that such solutions are as magnetically continuous in character as iron itself.

‘ In the next place, I think it is impossible to say that the medium interposed between the magnet and the suspended cylinder of fluid can cut off, or in any way affect the direct force of the former on the latter, so as to change the direction of its internal polarity. Let the tube be filled with the solution m , then if it be surrounded by the solution l , it will point as iron ; if the stronger solution n surround it, it will point as bismuth ; and with sufficient

¹ Phil. Mag. 1846, vol. xxix. p. 254.

care a succession of these fluids may be arranged as indicated in figs. 2, 3, where the outlines between the poles

FIG. 2.

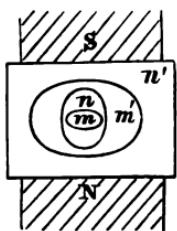
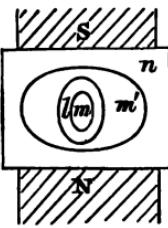


FIG. 3.



represent the forms of thin glass troughs, and the letters the solutions in them. In fig. 2 we see that the action on m is the same as that on m' , and the pointing of the two portions is the same, i.e. equatorial; neither has the action on m been altered by the power of the poles having to traverse n , m and n' ; and in fig. 3 we see, that, under like circumstances of the power, m' points as bismuth and m as iron, though they are the same solution with each other and with the former m m' solutions. No cutting off of power by the media could cause these changes; repetitions of position in the first case, and

inversions in the second. All that could be expected from any such interceptions would be perhaps diminutions of action, but not inversions of polarity; and every consideration indicates that all the portions of these solutions in the field at once have *like polarity*, i.e. like direction of force through them, and like internal condition; each solution in its complex arrangement being affected exactly in the same way and degree as if it filled the whole of the magnetic field, although in these particular arrangements it sometimes points like iron, and at other times like bismuth.

'These motions and pointings of the same or of different solutions, contain every action and indication which is supposed to distinguish the contrary polarities of paramagnetic and diamagnetic bodies from each other, and the solutions l and m in air repeat exactly the phenomena presented in air by phosphorus and platinum, which are respectively diamagnetic and paramagnetic substances.

But we know that these actions are due to the differential result of the masses of the moving or setting solution and of that (or the air) surrounding it. No structural or internal polarity, having opposite directions, is necessary to account for them. If, therefore, it is still said that the solution *m* has one polarity in *l* and the reverse polarity in *n*, that would be to make the polarity depend upon the *mass* of *m* independently of its particles; for it can hardly be supposed that the particles of *m* are more affected by the influence upon them of the surrounding medium (itself under like inductive action only, and almost insensible as a magnet) than they are by the dominant magnet.¹ It would be also to make the polarity of *m* as much, or more, dependent upon the surrounding medium than upon the magnet itself;—and it would be, to make the masses of *m* and *l* and even their *form* the determining cause of the polarity; which would remove polarity altogether from dependence upon internal molecular condition, and, I think, destroy the last remains of the usual idea. For my own part, I cannot conceive that when a little sphere of *m* in the solution *l* is attracted upon the approach of a given magnetic pole, and repelled under the action of the same pole when it is in the solution *n*, its particles are in the two cases polar in two opposite directions; or that if for a north magnetic pole it is the *near* side of the particles of *m* when in *l* that assume the south state, it is the *further* side which acquires the same state when the solution *l* is changed for *n*. Nor can I think that when the particles of *m* have the same

¹ If the polarity of the inner mass of solution is dependent upon that of the outer, and cannot be affected but through it, then why is not air and space admitted as being in effective magnetic relation to the bodies surrounded by them? How else could a distant body be acted upon by a magnet, if the inner solution of sulphate of iron is so acted on? Are we to assume one mode of action by contiguous masses of particles in one case, and another through distance in another case?

polar state in both solutions, the whole, as a mass, can have the opposite states.

‘ These differential results run on in one uninterrupted course from the extreme of paramagnetic bodies to the extreme of diamagnetic bodies ; and there is no substance within the series which, in association with those on each side of it, may not be made to present in itself the appearances and action which are considered as indicating the opposite polarities of iron and bismuth. How then is their case, in the one or the other condition, to be distinguished from the assumed polarity conditions of bismuth or of iron ?—only, I think, by assuming other points which beg the whole question. In the first place, it must be, or is assumed, that no magnetic force exists in the space around a magnet when it is in a vacuum, it being denied that the power either crosses or reaches a locality in that space until some material substance, as the bismuth or iron, is there. It is assumed that the space is in a state of magnetic darkness, an assumption so large, considering the knowledge we have of natural powers, and especially of dual forces, that there is none larger in any part of magnetic or electric science, and is the very point which of all others should be held in doubt and pursued by experimental investigation. It is as if one should say, there is no light or form of light in the space between the sun and the earth, because that space is invisible to the eye. Newton himself durst not make a like assumption even in the case of gravitation, but most carefully guards himself and warns others against it, and Euler¹ seems to follow him in this matter. Such an assumption, however, enables the parties who make it to dismiss the consideration of differential effects when bodies are placed in a vacuum, and to divide the bodies into the well-known

¹ Letters, &c. translated. Letter LXVIII., or pp. 260–262.

double series of paramagnetic and diamagnetic substances. But in the second place, even then, those who assume the reverse polarity of diamagnetic bodies, must assume also that the state set up in them by conduction is less favourable to either the exercise or the transmission of the magnetic force than the original unpolarised state of the bismuth; an assumption which is, I think, contrary to the natural action and final stable condition into which the physical forces tend to bring all bodies subject to them. That a magnet acting on a piece of iron should so determine and dispose of the forces as to make the magnet and iron mutually accordant in their action, I can conceive; but that it should throw the bismuth into a state which would make it repel the magnet, whereas if unaffected it should be so far favourable as to be at least indifferent, is what I cannot imagine to myself. In the third place, those who rest their ideas on *magnetic fluids*, must assume that in all diamagnetic cases, and in them only, the fundamental idea of their mutual action must not only be set aside but inverted, so that the hypothesis would be at war with itself; and those who assume that *electric currents* are the cause of magnetic effects, would have to give up the law of their inducing action (as far as we know it) in all cases of diamagnetism, at the very same moment when, if they approached the diamagnetic bismuth in the form of a spiral to the pole, they would have a current produced in it according to that law.'

3. ON THE EXISTENCE OF A MAGNETIC MEDIUM IN SPACE.

'These motions and pointings,' says Faraday, in the foregoing extract, 'contain every action and indication which is supposed to distinguish the contrary polarities of paramagnetic and diamagnetic bodies.' In the following letter I ventured to draw his attention to certain phenomena which the motions and pointings referred to did not seem to cover. Faraday, it will be observed, here passes from the *fact* of diamagnetic polarity, which is irrefutable, to the *theory* of magnetism in general. It was probably the perusal of Faraday's remarks that caused M. Weber to emphasise the distinction between fact and theory in his letter to me.

MY DEAR MR. FARADAY,—Few, I imagine, who read your memoir in the last number of the 'Philosophical Magazine,' will escape the necessity of reconsidering their views of magnetic action. We are so accustomed to regard the phenomena of this portion of science through the imagery with which hypothesis has invested them, that it is extremely difficult to detach symbols from facts, and to view the latter in their purity. This duty, however, is now forced upon us; for the more we reflect upon the results of recent scientific research, the more deeply must we be convinced of the impossibility of reconciling these results with our present theories. In the downfall of hypotheses thus pending, the great question of a universal

magnetic medium has presented itself to your mind. Your researches incline you to believe in the existence of such a medium, and lead you, at the same time, to infer the perfect identity of magnetism and diamagnetism.

In support and illustration of your views, you appeal to the following beautiful experiments:—Three solutions of proto-sulphate of iron are taken; the first, *l*, contains 4 grains; the second, *m*, 8 grains: and the third, *n*, 16 grains of the salt to a cubic inch of water. Enclosed in hollow globules of glass, all these solutions, when suspended in the air before the pole of a magnet, are attracted by the pole. You then place a quantity of the medium solution, *m*, in a proper vessel, immerse in it the globule containing the strong solution, *n*, and find that the latter is still attracted; but that when the globule containing the solution *l* is immersed, the latter is *repelled* by the magnetic pole. Substituting elongated tubes for spheres, you find that when a tube containing a solution of a certain strength is suspended in a weaker solution, between the two poles of a magnet, the tube sets from pole to pole; but that when the solution *without* the tube is stronger than that *within* it, the tube recedes from the pole and sets equatorial.

Here then, you state, are the phenomena of diamagnetism. It is maintained by some, that, to account for these phenomena, it is necessary to assume, in the case of diamagnetic bodies, the existence of a polarity the reverse of that of iron. But nobody will affirm that the mere fact of its being suspended in a stronger solution reverses the polarity of a magnetic liquid:—to account for the repulsion of the weak solution, when submerged in a stronger one, no such hypothesis is needed; why then should it be thought necessary in the case of so-called diamagnetic bodies? It is only by denying that space holds a medium which bears the same relation to

diamagnetic bodies that the stronger magnetic solution bears to the weaker one, that the hypothesis of a distinct diamagnetic polarity is at all rendered necessary.

The effects upon which the foregoing striking argument is based are differential ones, and are embraced, as already observed by M. E. Becquerel, by the so-called principle of Archimedes. This principle, in reference to the case before us, affirms that the body immersed in the liquid is attracted by a force equal to the difference of the attractions exerted upon the liquid and the body immersed in it. Hence, if the attraction of the liquid be less than that of the immersed body, the latter will approach the pole; if the former attraction be the greater, the immersed body recedes from the pole, and is apparently repelled. The action is the same as that of gravity upon a body plunged in water; if the body be more forcibly attracted bulk for bulk, than the water, it sinks; if less forcibly attracted, it rises; the mechanical effect being the same as if it were repelled by the earth.

The question then is, are all magnetic phenomena the result of a differential action of this kind? Does space contain a medium less strongly attracted than soft iron, and more strongly attracted than bismuth, thus permitting of the approach of the former, but causing the latter to recede from the pole of a magnet? If such a medium exists, then diamagnetism, as you incline to believe, merges into ordinary magnetism, and 'the polarity of the magnetic force,' in iron and in bismuth, is one and the same.

Pondering upon this subject a few evenings ago, and almost despairing of seeing it ever brought to an experimental test, a thought occurred to me which, when it first presented itself, seemed to illuminate the matter. Such illuminations vanish in nine cases out of ten before the test of subsequent criticism; but the thought referred to,

having thus far withstood the criticism brought to bear upon it, I am emboldened to submit it to you for consideration.

I shall best explain myself by assuming that a medium of the nature described exists in space, and pursuing this assumption to its necessary consequences.

Let a cube, formed from the impalpable dust of carbonate of iron,¹ which has been forcibly compressed in one direction, be placed upon the end of a torsion beam, and first let the line in which the pressure has been exerted be in the direction of the beam. Let a magnet, with its axis at right angles to the beam, and hence also at right angles to the line of pressure, be brought to bear upon the cube. The cube will be attracted, and the amount of this attraction, at any assigned distance, may be accurately measured by the torsion of the wire from which the beam depends. Let this attraction, expressed in degrees of torsion, be called α . Let the cube now be turned round 90° , so that the line of pressure shall coincide with the direction of the axis of the magnet, and let the attraction $\acute{\alpha}$ in this new position be determined as in the former instance. On comparison it will be found that $\acute{\alpha}$ exceeds α ; or, in other words, that the attraction of the cube is strongest when the force acts parallel to the line of compression.

Instead of carbonate of iron we might choose other substances of a much feebler magnetic capacity, with precisely the same result. Let us now conceive the magnetic capacity of the compressed cube to diminish gradually, and thus to approach the capacity of the medium in which, according to our assumption, the carbonate of iron is supposed to be immersed. If it were a perfectly homogeneous cube, and attracted with the

¹ For an ample supply of this most useful mineral I am indebted to the kindness of J. Kenyon Blackwell, Esq., F.G.S.

same force in all directions, we should at length arrive at a point, when the *magnetic weight* of the cube, if I may use the term, would be equal to that of the medium, and we should then have a substance which, as regards magnetism, would be in a condition similar to that of a body withdrawn from the action of gravity in Plateau's experiments. Such a body would be neither attracted nor repelled by the magnet. In the compressed cube, however, the magnetic weight varies with the direction of the force. Supposing the magnetic weight, when the force acts along the line of compression, to be equal to that of the medium, then if the force acted across the line of compression, the magnetic weight of the cube would be less than that of the medium. Acted upon in the former direction, the cube would be a neutral body ; acted upon in the latter direction, it would be a diamagnetic body, If the magnetic capacity of the cube diminish still further it will, according to your hypothesis, become wholly diamagnetic. Now it is evident, supposing the true magnetic excitement to continue, that the cube, when acted on by the magnet in the direction of compression, *will approach nearer to the magnetic weight of the medium* in which we suppose it immersed, than when the action is across the said line ; and, hence, the repulsion of the cube, when the force acts along the line of compression, must be *less* than when the force acts across it.

Reasoning thus from the assumption of a magnetic medium in space, we arrive at a conclusion which can be brought to the test of experiment. So far as I can see at present, the assumption is negatived by this test ; for in diamagnetic bodies the repulsion along the line in which the pressure is exerted is proved by experiment to be a *maximum*. An ordinary magnetic excitement could not, it appears to me, be accompanied by this effect.

The subject finds further, and perhaps clearer, elucidation

tion in the case of isomorphous crystals. It is not, I think, questioned at present, that the deportment of crystals in the magnetic field depends upon their molecular structure; nor will it, I imagine, be doubted, that the molecular structure of a complete crystal of carbonate of iron is the same as that of an isomorphous crystal of carbonate of lime. In the architecture of the latter crystal, calcium simply takes the place which iron occupies in the former. Now a crystal of carbonate of iron is attracted most forcibly when the attracting force acts parallel to the crystallographic axis. Let such a crystal be supposed to diminish gradually in magnetic capacity, until finally it attains a magnetic weight, *in a direction parallel to its axis*, equal to that of the medium in which we assume it to be immersed. Such a crystal would be indifferent, if the force acted parallel to its axis, but would be repelled, if the force acted in any other direction. If the magnetic weight of the crystal diminish a little further, it will be repelled in all directions, or, in other words, will become diamagnetic; but it will then follow, that the repulsion in the direction of the axis, if the nature of the excitement remain unchanged, will be less than in any other direction. In other words, a diamagnetic crystal of the form of carbonate of iron will, supposing magnetism and diamagnetism to be the same, be repelled with a *minimum* force when the repulsion acts parallel to the axis. Here, as before, we arrive at a conclusion which is controverted by experiment; for the repulsion of a crystal of carbonate of lime is a *maximum* when the repelling force acts along the axis of the crystal. Hence I would infer that the excitement of carbonate of iron cannot be the same as that of carbonate of lime.

Such are the reflections which presented themselves to my mind on the evening to which I have referred. I now submit them to you as a fraction of that thought which

your last memoir upon this great question will assuredly awaken.

Believe me,

Dear Mr. Faraday,

Yours very faithfully,

JOHN TYNDALL.

ROYAL INSTITUTION:

February, 1855.

[To this letter Faraday wrote a brief reply, Phil. Mag., vol. ix. p. 253. I fear I failed to make clear to him the gist of my argument. Further communications on this subject were published by Prof. Williamson and Dr. Hirst in the Philosophical Magazine.]

4. FARADAY'S LETTER TO MATTEUCCI.

THE following charming letter, extracted from Dr. Bence Jones's 'Life and Letters of Faraday,' shows the views of diamagnetic polarity entertained by Faraday in 1855. It was written prior to the publication of the Bakerian Lecture for that year; but I have no reason to believe that the views here expressed were ever changed.

‘ November 2, 1855.

‘ MY DEAR MATTEUCCI,—When I received your last of October 23, I knew that Tyndall would return from the country in a day or two, and so waited until he came. I had before that told him of your desire to have a copy of his paper, and I think he said he would send it to you; I have always concluded he did so, and therefore thought it best to continue the same open practice and show him your last letter, note and all.

‘ As I expected, he expressed himself greatly obliged by your consideration, and I have no doubt will think on, and repeat, your form of experiment; but he wished you to have no difficulty on his account. I conclude he is quite assured in his own mind, but does not for a moment object to counter views, or to their publication; and I think feels a little annoyed that you should imagine for a moment that he would object to or be embarrassed by your publication. I think in that respect he is of my mind, that we are all liable to error, but that we love the truth,

and speak only what at the time we think to be truth ; and ought not to take offence when proved to be in error, since the error is not intentional; but be a little humbled and so turn the correction of the error to good account. I cannot help thinking that there are many apparent differences amongst us, which are not differences in reality. I differ from Tyndall a good deal in phrases, but when I talk with him I do not find that we differ in facts. That phrase polarity in its present undefined state is a great mystifier.

‘ Well ! I am content, and I suppose he is, to place our respective views before the world, and there leave them. Although often contradicted, I do not think it worth while reiterating the expressions once set forth or altering them, until I either see myself in the wrong or misrepresented, and even in the latter case I let many a misrepresentation pass. Time will do justice in all these cases.

‘ One of your letters asks me, what do you conceive the nature of the lines of magnetic force to be ? I think it wise not to answer that question by an assumption, and therefore have no further account to give of such physical lines than that already given in my various papers. See that referred to already in the “ Philosophical Magazine ” (3301–3305) ; and I would ask you to read also 3299, the last paragraph in a paper in the “ Philosophical Magazine,” June 1852, which expresses truly my present state of mind.

‘ But a physical line of force may be dealt with experimentally without our knowing its intimate physical nature. A ray of light is a physical line of force ; it can be proved to be such by experiments made whilst it was thought to be an emission, and also by other experiments made since it has been thought to be an undulation. Its physical character is not proved either by the one view or the other (one of which must be, and both may be wrong), but it is proved by the

time it takes in propagation, and by its curvatures, inflections, and physical affections. So with other physical lines of force, as the electric current ; we know no more of the physical nature of the electric lines of force than we do of the magnetic lines of force ; we fancy, and we form hypotheses, but unless these hypotheses are considered equally likely to be false as true, we had better not form them ; and therefore I go with Newton when he speaks of the physical lines of gravitating force (3305 note), and leave that part of the subject for the consideration of my readers.

' The use of lines of magnetic force (without the physical) as true representations of nature, is to me delightful, and as yet never failing ; and so long as I can read your facts, and those of Tyndall, Weber, and others by them, and find they all come into one harmonious whole, without any contradiction, I am content to let the erroneous expressions, by which they seem to differ, pass unnoticed. It is only when a fact appears that they cannot represent that I feel urged to examination, though that has not yet happened. All Tyndall's results are to me simple consequences of the tendency of paramagnetic bodies to go from weaker to stronger places of action, and of diamagnetic bodies to go from stronger to weaker places of action, combined with the true polarity or direction of the lines of force in the places of action.

' These principles, or rather laws, explain to me all those movements obtained by Tyndall against which your note is directed, and therefore I do not see in his experiments any proofs of a defined or inverse polarity in bismuth, beyond what we had before. He has worked out well the antithetical relations of paramagnetic and diamagnetic bodies, and distinguished mixed actions which by some have been much confused ; but the true nature of polarity, and whether it is the same or reversed in the two

classes, is to my mind not touched. What a quantity I have written to you, all of which has no doubt been in your own mind, and tried by your judgment! Forgive me for intruding it.

‘Ever truly yours,
‘M. FARADAY.’

The circumstances in which this letter originated are these. On the receipt of my paper, ‘On the Nature of the Force by which Bodies are repelled from the Poles of a Magnet,’ Matteucci undertook to repeat the experiments there recorded, but failed to obtain the results. He considered the memoir a tissue of error from beginning to end, and thought my character as a scientific man so gravely compromised that he wrote to ask Faraday for advice as to how he ought to act under the circumstances. Faraday showed me Matteucci’s letter, and the result of our conversation regarding it is stated by Faraday himself. Weeks, it may have been months, elapsed without my hearing anything further about the matter; when at length a terse, frank letter reached me direct from Matteucci, the substance of which was this:—‘I have written to Faraday, to Grove, and to Wheatstone, stating that your experiments were wrong. I now wish to give you the opportunity of correcting me, and of saying to these gentlemen that I have repeated all your experiments and found them true to the letter.’

I think it probable that as regards diamagnetic polarity, Faraday and myself were sometimes looking at two different things. I looked to that doubleness of action in which the term polarity originated, and which causes electricity, as well as magnetism, to be regarded as a polar force. Faraday, I doubt not, had his mind fixed upon his lines of magnetic force. To this conception, however, though it formed the guiding light of his researches, he never gave

a mechanical form. Hence arose his difficulty in dealing with the phenomena exhibited by crystals in the magnetic field. Refusing the clue of polarity, and holding magnecrystallic phenomena to be products of a new force which was neither attractive nor repulsive, his difficulty was insurmountable. His thoughts, nevertheless, dwelt in the profoundest depths of the subject. His great discovery of the rotation of the plane of polarisation had connected the force of magnetism with the luminiferous ether ; and this future investigators will probably prove to be the domain of all magnetic action.¹ In the sense, however, in which the term polarity, as applied to magnetic phenomena, has been hitherto understood—in other words, as a matter of fact—the polarity of the diamagnetic force is, I submit, conclusively demonstrated.

¹ A conclusion to which the researches of Thomson and Maxwell even now distinctly point.

5. CHANGE OF FORM BY MAGNETISATION.

WISHING in 1855 to make the comparison of magnetic and diamagnetic phenomena as thorough as possible, I sought to determine whether the act of magnetisation produces any change of dimensions in the case of bismuth, as it is known to do in the case of iron. The action, if any, was sure to be infinitesimal, and I therefore cast about for a means of magnifying it. The idea which appeared most promising was to augment in the first instance by a lever the small amount of change expected, and to employ the augmented effect to turn the axis of a rotating mirror. By making the axis small enough it was plain that an infinitesimal amount of rectilinear motion might be caused to produce a considerable amount of angular motion. This I proposed to observe by a telescope and scale after the method of Gauss. I consulted Mr. Becker, and, thanks to his great intelligence and refined mechanical skill, I became the possessor of the apparatus now to be described.

A B (fig. 3) is the upper surface of a massive block of Portland stone. It is 21 inches wide, 13 inches deep, and 29 inches high. In it are firmly fixed two cylindrical brass pillars, c c, 1 inch in diameter and 35 inches in height. Over the pillars pass the two clamps, o o', and from the one to the other passes a cylindrical cross bar, 11 inches long and $\frac{3}{4}$ of an inch wide. This cross bar is capable of two motions; the first up and down the two pillars c c, parallel to itself; the second being a motion

FIG. 1.



FIG. 2.

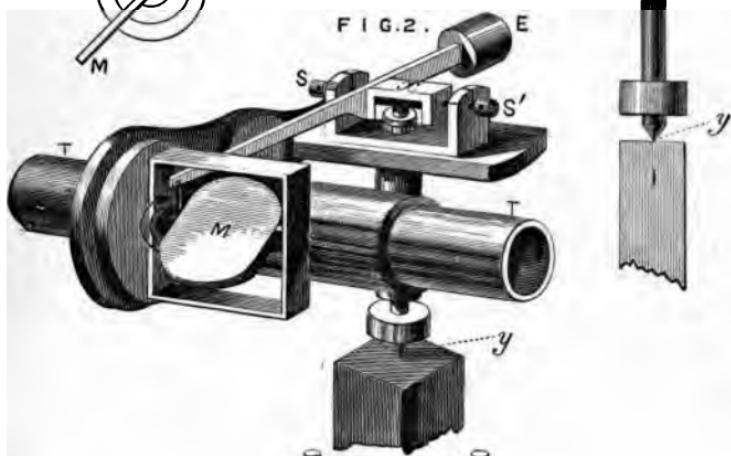
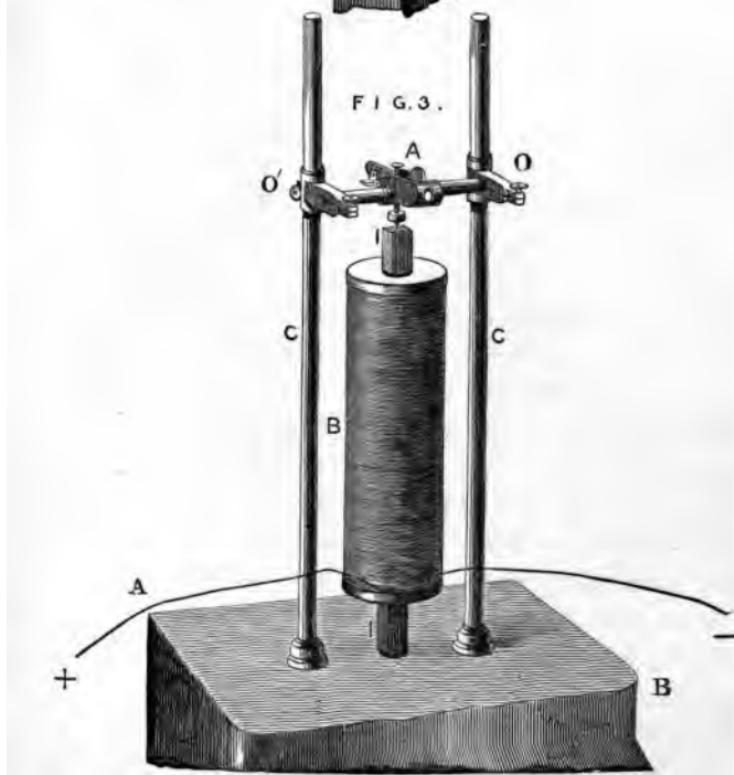


FIG. 3.



round its own axis. To this cross piece is attached the magnifying apparatus A.

The bar to be examined is set upright between the two pillars; being fixed firmly into a leaded screw imbedded in the Portland stone. It is surrounded by an electro-magnetic helix B. On the top of the bar I rests one end of a small cylindrical brass rod, with pointed steel ends. This rod fits accurately into a brass collar, moving up and down in it with the least possible friction. The other point of the rod presses against a plate of agate very close to a pivot round which the plate can turn. The agate plate is attached to a brass lever 2·1 inches long, whose fulcrum is the pivot just mentioned. Any motion of the point against which the rod presses is magnified about fifty times at the end of the lever. From this end passes a piece of fine steel fibre round the axis of a rotating mirror, which turns as the end of the lever moves. The mirror rotates with its axis. For accurate experiments an illuminated vertical scale is placed at a distance of about twelve feet from the mirror, which is observed through a telescope placed beside the scale. The magnifying apparatus is shown in detail in fig. 2, where M is the mirror; s and s' two centre-screws, whose points constitute the pivot round which the lever turns; E is a small counter-weight; T T is the cross-piece to which the magnifying apparatus is attached. A naked section of the magnifying apparatus is given in fig. 1. I is the bar to be magnetised, F the brass rod with the pointed steel ends, divested of its collar, one of its ends pressing against the plate of agate near the pivot x, and the other resting upon the bar of iron at y. From the end L of the lever the steel fibre passes round the axis a of the mirror M. When the bar I changes its length, the motion at L turns the mirror; and when I resumes its primitive length, the

mirror is brought back to its first position by the spiral hair-spring shown in the figure.

Biot found it impossible to work at his experiments on sound during the day in Paris; he was obliged to wait for the stillness of night. With the instrument just described I found it almost equally difficult to make accurate experiments in London. Take a single experiment in illustration. The mirror was fixed so as to cause the cross-hair of the telescope to cut the number 727 on the scale; a cab passed while I was observing—the mirror quivered, obliterating the distinctness of the figure, and the scale slid apparently through the field of view and became stationary at 694. I went upstairs for a book; a cab passed, and on my return I found the cross-hair at 686. A heavy waggon then passed, and shook the scale down to 420. Several carriages passed subsequently, after which the figure on the scale was 350. In fact, so sensitive is the instrument that long before the sound of a cab is heard its approach is heralded by the quivering of the figures on the scale.

Various alterations which were suggested by the experiments were carried out by Mr. Becker, and the longer I worked with it the more mastery I obtained over it; but I did not work with it sufficiently long to perfect its arrangement. Some of the results, however, may be stated here.

At the beginning of a series of experiments the scale was properly fixed, and the pressure of the pointed vertical rod *r*, fig. 1, on the end of the iron bar, *I*, so regulated as to give the mirror a convenient position; then, before the bar was magnetised, the figure cut by the cross-hair of the telescope was read off. The circuit was then established, and a new number, depending on the altered length of the bar by its magnetisation, started into view. Then the circuit was interrupted, and the return of the

mirror towards its primitive position was observed. The mirror, as stated, was drawn back to its first position by the spiral hair-spring shown in fig. 1. Here are some of the results :—

	Figure of scale.
Bar unmagnetised	577
„ magnetised	470
„ unmagnetised	517

Here the magnetisation of the bar produced an elongation expressed by 107 divisions of the scale, while the interruption of the circuit produced only a shrinking of 47 divisions. There was a tendency on the part of the bar, or of the mirror, to persist in the condition super-induced by the magnetism. The passing of a cab in this instance caused the scale to move from 517 to 534—that is, it made the shrinking 64 instead of 47. Tapping the bar produced the same effect.

The bar employed here was a wrought-iron square core, 1·2 inch a side and two feet long.

The following tables will sufficiently illustrate the performance of the instrument in its present condition. In each case are given the figures observed before closing, after closing, and after interrupting the circuit. Attached to each table, also, are the lengthening produced by magnetising and the shortening consequent on the interruption of the circuit :—

Circuit.	Scale 10 cells.	Circuit.	Scale 20 cells.
Open . .	647	Open . .	653
Closed. .	516 131 elongation.	Closed. .	475 188 elongation.
Broken . .	581 65 return.	Broken . .	579 144 return.
Open . .	637	Open . .	638
Closed. .	509 128 elongation.	Closed. .	452 186 elongation.
Broken . .	579 70 return.	Broken . .	568 116 return.
Open . .	632	Open . .	632
Closed. .	491 141 elongation.	Closed. .	472 160 elongation.
Broken . .	568 77 return.	Broken . .	561 89 return.

These constitute but a small fraction of the number of experiments actually made. There are, I may add, very decided indications that the amount of elongation depends on the molecular condition of the bar. For example, a bar taken from a mass used in the manufacture of a great gun at the Mersey Iron-works suffered changes on magnetisation and demagnetisation considerably less than those recorded here.¹ With bars of bismuth, however strong might be the magnetism, no change whatever was observed.

¹ I owe these bars to the liberality of the proprietors of the Mersey Iron-works, through the friendly intervention of Mr. Mallet.

6 THE POLYMAGNET.

THE polymagnet consists of an arrangement of two horse-shoe electro-magnets, a helix of covered copper wire disposed between them, and suitable means of suspension.

A section of one of the electro-magnets and its surrounding spirals is given, fig. 1. *ab*, *cd* are two cylindrical cores of soft iron, which are united by a cross-piece of the same material, *ef*. Through the cross-piece pass the strong screws *g* and *h* into the cores, and by them the ends *b* and *d* of the cores, which are accurately planed so as to ensure perfect contact with the cross-piece, are attached to the latter. The diameter of the cores is 1·125 inch, and their distance apart, from centre to centre, 4·85 inches; the cross-piece *ef* is drawn in proportion.

Round each core is a helix of copper wire, overspun with cotton, saturated with shell-lac. In winding the helix, two lengths of wire, one covered with red cotton and the other with green, are laid side by side and coiled as a single wire. The diameter of the wire is 0·1 of an inch, and the weight of it which surrounds each limb of the magnet is 12 lbs. For all four limbs, therefore, a weight of 48 lbs. is made use of.

The second electro-magnet is in every respect similar to the one just described.

Fig. 2 is a front view of a flat helix of covered copper wire, intended to be placed between the two electro-magnets; it has an internal diameter, *ab*, of 1 inch; an external diameter, *cd*, of 8 inches, and measures along its

Fig. 1.

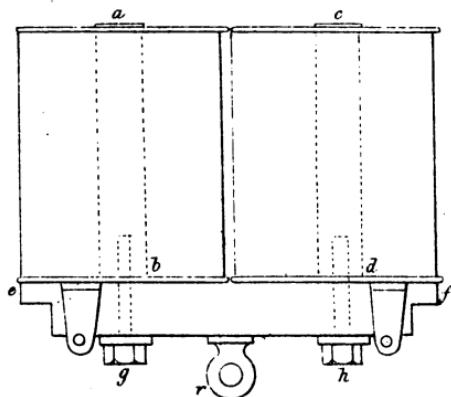


Fig. 2.

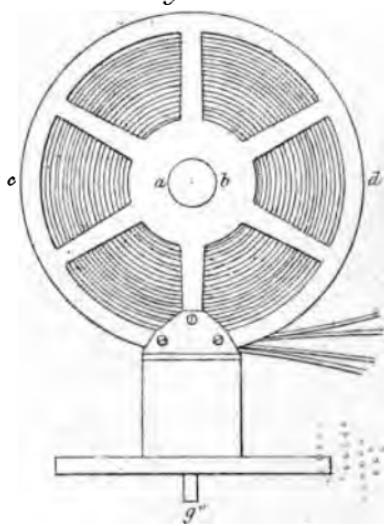






Fig. 3.

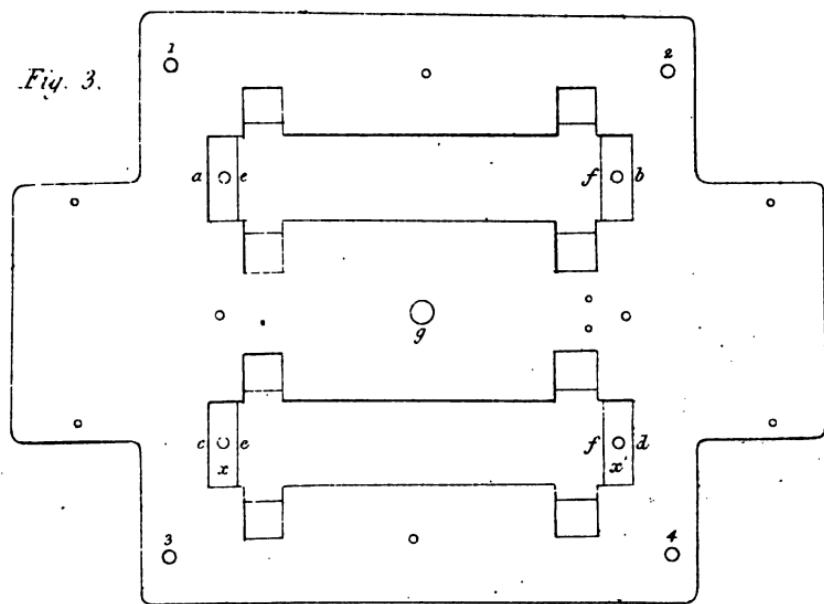
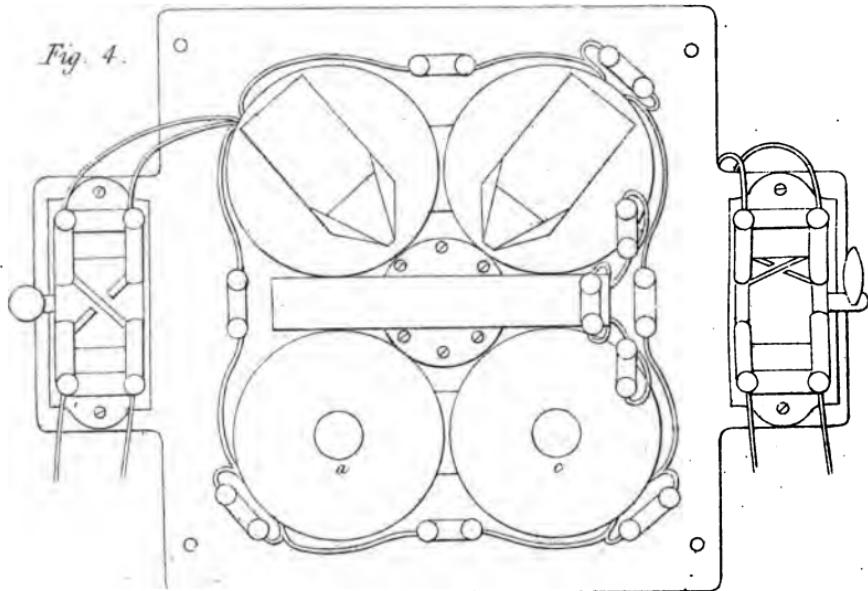


Fig. 4.



axis 1·15 inch. The diameter of its wire is 0·065 of an inch, and its weight is 6 lbs.; it is wound so as to form a double coil, as in the case of the electro-magnets. The radial strips, and central and surrounding ring seen in the figure, are of brass, and hold the coils of the helix compactly together.

Fig. 3 represents a stout slab of mahogany which supports the apparatus. *ab*, *cd* are hollows cut in the slab to receive the cross-pieces of the two electro-magnets; from *e* to *f* the slab is cut quite through, the cross-pieces merely resting on the portions between *f* and *b*, *f* and *d*, &c. The small apertures at *x* *x'* show where the screws enter which attach the cross-piece to the slab of wood. The central aperture at *g* shows where the pin *g''* of the helix, fig. 2, enters, the helix being supported on the central portion of the board. Right and left are two projections for the reception of two current reversers, which will be described immediately. The apertures 1, 2, 3, 4 are for the reception of pins projecting from the bottom of a glass case intended to cover the whole apparatus.

When the magnets and central helix are fixed in their places and locked down upon, their appearance is that represented in fig. 4; at *a* and *c* the tops of the cores are seen, the movable soft iron poles which belong to them being removed; the two ends of the other electro-magnet bear two such poles, each formed from a parallelopiped 4·5 inches long, 2 inches wide, and 1·25 inch high, having one end bevelled off so as to render it pointed, the other end being suffered to remain flat. The distance between those movable masses may be varied, and the body to be examined may be suspended either between *surfaces* or *points*, according to the nature of the experiment. The horizontal projections of the current reversers are seen to the right and left in fig. 4.

Simplicity and efficiency being the objects aimed at, a

current reverser was devised which fulfils these conditions. A front view of the instrument is given in fig. 5, and its horizontal projection in fig. 6. Q is the section of a quadrant of box-wood, which is capable of being turned by the handle HP ; ab is the section of a strip of brass laid on the periphery of the quadrant; cd is a shorter strip similarly laid on; between b and c is a gap, formed of the wood of the quadrant itself, or of a piece of ivory or glass inlaid; s and s' are two brass springs, which are shown resting upon the strips of brass ab and cd ; $M M'$, fig. 5, are two clamps secured to the wooden pillars O and O' by screws S , which pass up through the latter. The plan, fig. 6, corresponds to the section, fig. 5. From b , fig. 6, a strip of brass crosses to c' , while a second strip crosses from c to b' , the strips being insulated from each other at R . Supposing, then, the two clamps M and L to be connected with the two poles of a galvanic battery, the current entering at M would flow along the spring s to b , thence to c' , and finally along the spring s' to the clamp L' : in like manner the current entering at L would attain the clamp M' . In this position of things the handle of the instrument leans to the left, as in fig. 5. If the current is to be interrupted, the handle is set vertical; for when the handle is in this position, the spring s' rests upon the non-conducting surface bc , and the circuit is broken. If it be desired to send the current direct from L to L' , and from M to M' , the handle is turned to the right; the two springs s s' rest then upon the self-same strip of brass ab , and there is direct metallic communication between L and L' , and between M and M' . This reverser has been tested practically, and found extremely convenient. It is very similar to an instrument devised by Professor Reusch, but simpler and more easily constructed.

The whole instrument, surrounded by its glass case, is shown in perspective in fig. 8. The magnets are visible,

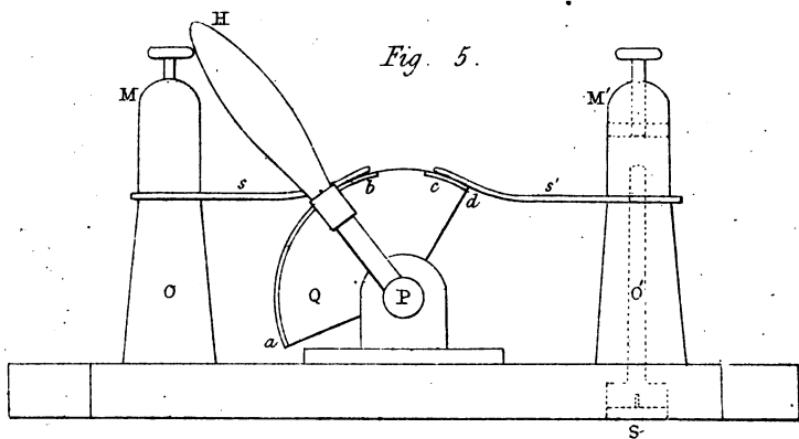


Fig. 6.

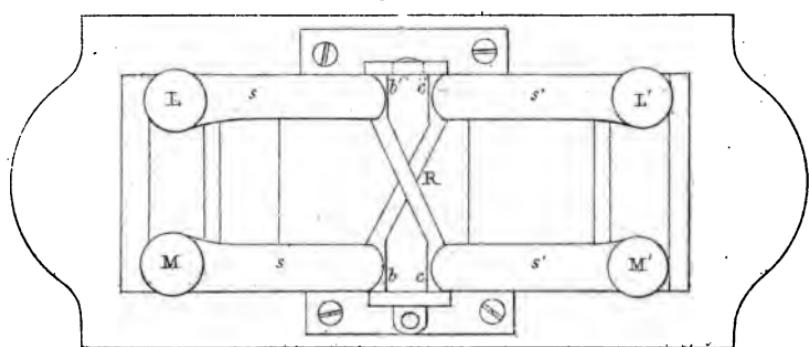
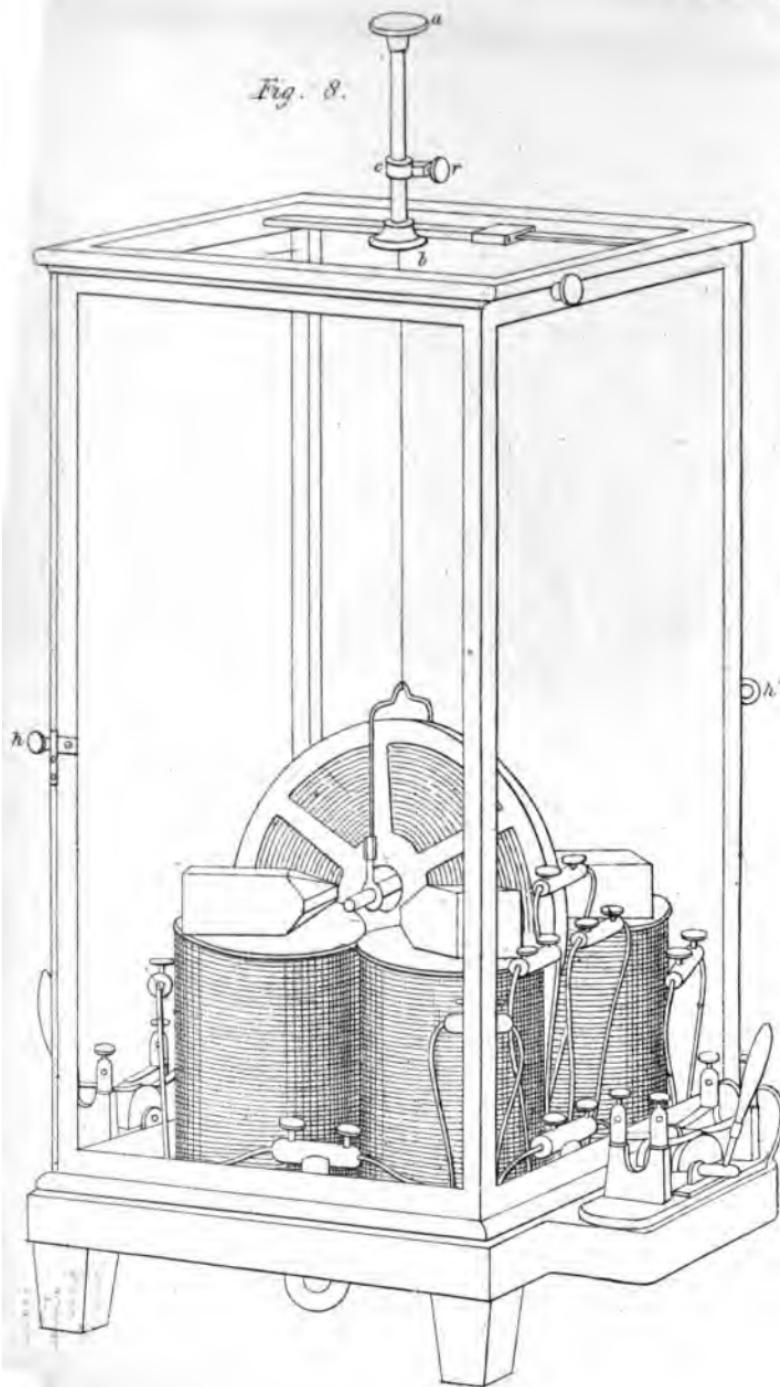






Fig. 8.



with the movable poles resting upon them; in the centre is seen the helix sketched in fig. 2, and within the helix a bismuth bar supported by several fibres of unspun silk attached to the central rod which passes through the top of the glass case. The manner of suspension of the bismuth will be understood from the drawing, certain practical artifices which suggest themselves when the drawing is attentively inspected being introduced to facilitate the placing of the axis of the bar accurately along the axis of the surrounding helix. The current reversers are seen *without* the case; two opposite sides of the latter can be opened by the handles h and h' , so that free and easy access to the interior is always secured.

Experiments to be made with the Polymagnet.

1. All the experiments that are usually made with an upright electro-magnet.
2. The various portions of the instrument may with great facility be lifted separately out of the case. Fig. 1 shows one of the electro-magnets thus removed. A rope can be passed through a ring r in the cross-piece. Adjacent to the screws g and h are two perforated plates of brass which are attached to the brass reels of the helices. By passing a pin through the holes shown in the figure, the helices are prevented from slipping off the cores when the magnet is turned upside down. Attaching the rope to a hook in the ceiling, or to a strong frame made for the purpose, experiments on the lifting power of the magnet may be made.

3. While one of the magnets is suspended as last described, the other, which is of exactly the same size, can be brought up against it, the free ends of the four cores being thus in contact. The same current being sent through both magnets, we have the mutual attraction of two electro-magnets, instead of the attraction of an electro-

magnet for an armature, as supposed in the last experiment. The arrangement just described is indeed precisely that devised by M. Pouillet in the construction of a powerful electro-magnet for the Faculty of Sciences at Paris. To the cross-piece of the second magnet a ring is also attached, from which weights can be suspended.

4. The cross-pieces can be removed by withdrawing the screws *g* and *h*, and the helices may be made use of singly with their corresponding bar-magnets. As two wires surround each coil, one of them may be used to exhibit the induced currents developed by the other. The phenomena of the extra-current may also be studied, and the remarkable effect produced on the spark of the extra-current by connecting the two ends of one of the wires of the other helix, may be exhibited.

5. If an ordinary feebly magnetic bar be suspended between one pair of poles, and an ordinary diamagnetic bar between the other pair, on sending the same current round both magnets, the former sets itself parallel, while the latter sets itself perpendicular to the polar line. The phenomena of magnetism and diamagnetism are thus made to address the eye simultaneously.

6. In the same way, if a normal magnetic bar be suspended between one pair of poles, and an abnormal magnetic bar between the other pair, the antithesis of their deportment may be made manifest. The same antithesis is exhibited when we compare a normal diamagnetic bar with an abnormal one.

7. And when between one pair of poles is suspended a normal magnetic bar, and between the other pair an abnormal diamagnetic one, the apparent identity of deportment of both bars is rendered evident at once. The same identity is shown when we compare the abnormal magnetic bar with the normal diamagnetic one.

8. Causing the points to face each other, instead of the

flat ends of the poles, and observing the directions given in the Bakerian Lecture for 1855, the curious phenomena of rotation on raising or lowering the body from between the points, first observed by M. Plücker, and explained in the paper referred to, may be exhibited.

9. To show that a bar of bismuth, suspended within a helix and acted upon by magnets, presents phenomena exactly analogous to those of soft iron, only always in opposite directions, let the flat helix be mounted between the two electro-magnets. The bar of bismuth used in experiments with the instrument just described is 6 inches long and 0·4 of an inch in diameter. Suspended so as to swing freely within the helix, its ends, to which the diamagnetic excitement is freely propagated from the centre, where the bar is surrounded by the flat coil, lie between the movable poles which rest upon the electro-magnetic cores. Four poles are thus brought simultaneously to bear upon the bar of bismuth, and its action is thereby rendered both prompt and energetic. The two poles to the right of the bar must both be of the same name, and the two to the left of the bar of the opposite quality. If those to the right be both north, those to the left must be both south, and *vice versa*. On sending a current from 10 or 15 cells round the helix, and exciting the magnets by a battery of 4 or 5 cells, the current reversers place the deflections of the bar entirely under the experimenter's control. Changing, by means of its reverser, the direction of the current in the helix, a change of deflection is produced; the same is effected if the polarity of the magnets be changed by the reverser which belongs to them.

10. To those acquainted with what has been done of late years in diamagnetism, numerous other experiments will suggest themselves. The antithesis of two isomorphous crystals, one magnetic and the other diamagnetic, the

general phenomena of magnecrystallic action, and the analogous effects produced by pressure, may all be exhibited.

11. By mounting two helices of the electro-magnet, one upon the other, a coil of double length is obtained, and two such coils may be formed from the four just described. For the additional expense of the iron merely, a single electro-magnet, far more powerful than either of the others, because excited by twice the quantity of coil, may be obtained.

The instrument above described was constructed by Mr. Becker, of Newman Street, and its cost is about 24*l.* It was not my intention originally to have so much wire round the electro-magnets; and the effects may also be obtained with a smaller central coil. I have no doubt that with 8 lbs. of wire round each limb of the electro-magnets, and a central coil weighing 4 lbs., the experiments might be exhibited with perfect distinctness. A sensible diminution of cost would of course accompany this diminution of material and labour.

7. STEEL MOULDS FOR COMPRESSION.

THE steel moulds employed in my experiments on compression are here represented. To prevent all magnetic contamination they were coated galvano-plastically with copper.

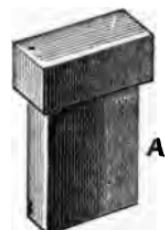
FIG. 1.



FIG. 2.



FIG. 3.



B'



B



C'



Y



C

In fig. 1, A', B', C' represent the three parts of the mould used for forming cubes of compressed bismuth, whether of solid metal or in powder. Fig. 3, A, B, C, represent the three parts of the mould employed to form

rectangular bars. In fig. 2, x, the three parts of fig. 1 are put together. In fig. 2, y, the three parts of fig. 3 are put together. In experimenting, b' or b is first set upon its base, c' or c; the solid or the powder is then placed within b' or b, the plunger a' or a is then introduced, and the whole squeezed between the plates of a small hydraulic press. The compressed substance is of course firmly jammed in the mould, and to remove it a *perforated* base (not shown in the figure) is employed, on which b' or b is placed, and the squeezed metal forced out by the plunger a' or a, acted on by the hydraulic press. The drawings are half the linear size of the moulds themselves.

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